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**UTILITY PATENT APPLICATION TRANSMITTAL  
(Small Entity)**

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Docket No.  
89589.113000

Total Pages in this Submission

**TO THE ASSISTANT COMMISSIONER FOR PATENTS****Box Patent Application  
Washington, D.C. 20231**

Transmitted herewith for filing under 35 U.S.C. 111(a) and 37 C.F.R. 1.53(b) is a new utility patent application for an invention entitled:

**METHOD FOR TRACKING MOTION OF A FACE**

and invented by:

**A. Tanju Erdem**If a **CONTINUATION APPLICATION**, check appropriate box and supply the requisite information:☐ **Continuation** ☐ **Divisional** ☐ **Continuation-in-part (CIP)** of prior application No.: \_\_\_\_\_

Which is a:

☐ **Continuation** ☐ **Divisional** ☐ **Continuation-in-part (CIP)** of prior application No.: \_\_\_\_\_

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☐ **Continuation** ☐ **Divisional** ☐ **Continuation-in-part (CIP)** of prior application No.: \_\_\_\_\_

Enclosed are:

**Application Elements**

1. ☒ Filing fee as calculated and transmitted as described below
2. ☒ Specification having 41 pages and including the following:
  - a. ☒ Descriptive Title of the Invention
  - b. ☐ Cross References to Related Applications (if applicable)
  - c. ☐ Statement Regarding Federally-sponsored Research/Development (if applicable)
  - d. ☐ Reference to Microfiche Appendix (if applicable)
  - e. ☒ Background of the Invention
  - f. ☒ Brief Summary of the Invention
  - g. ☒ Brief Description of the Drawings (if drawings filed)
  - h. ☒ Detailed Description
  - i. ☒ Claim(s) as Classified Below
  - j. ☒ Abstract of the Disclosure

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**Application Elements (Continued)**

3. ☒ Drawing(s) *(when necessary as prescribed by 35 USC 113)*  
a. ☒ Formal      b. ☐ Informal      Number of Sheets 12
4. ☒ Oath or Declaration  
a. ☒ Newly executed *(original or copy)*      ☐ Unexecuted  
b. ☐ Copy from a prior application (37 CFR 1.63(d)) *(for continuation/divisional application only)*  
c. ☒ With Power of Attorney      ☐ Without Power of Attorney  
d. ☐ DELETION OF INVENTOR(S)  
Signed statement attached deleting inventor(s) named in the prior application,  
see 37 C.F.R. 1.63(d)(2) and 1.33(b).
5. ☐ Incorporation By Reference *(usable if Box 4b is checked)*  
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under  
Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby  
incorporated by reference therein.
6. ☐ Computer Program in Microfiche
7. ☐ Genetic Sequence Submission *(if applicable, all must be included)*  
a. ☐ Paper Copy  
b. ☐ Computer Readable Copy  
c. ☐ Statement Verifying Identical Paper and Computer Readable Copy

**Accompanying Application Parts**

8. ☐ Assignment Papers *(cover sheet & documents)*
9. ☐ 37 CFR 3.73(b) Statement *(when there is an assignee)*
10. ☐ English Translation Document *(if applicable)*
11. ☒ Information Disclosure Statement/PTO-1449      ☒ Copies of IDS Citations
12. ☐ Preliminary Amendment
13. ☒ Acknowledgment postcard
14. ☒ Certificate of Mailing  
☐ First Class      ☒ Express Mail *(Specify Label No.):* EL407177136US

# UTILITY PATENT APPLICATION TRANSMITTAL (Small Entity)

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## Accompanying Application Parts (Continued)

15. ☐ Certified Copy of Priority Document(s) (if foreign priority is claimed)
16. ☒ Small Entity Statement(s) - Specify Number of Statements Submitted: 1
17. ☐ Additional Enclosures (please identify below):

## Request That Application Not Be Published Pursuant To 35 U.S.C. 122(b)(2)

18. ☒ Pursuant to 35 U.S.C. 122(b)(2), Applicant hereby requests that this patent application not be published pursuant to 35 U.S.C. 122(b)(1). Applicant hereby certifies that the invention disclosed in this application has not and will not be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication of applications 18 months after filing of the application.

### Warning

**An applicant who makes a request not to publish, but who subsequently files in a foreign country or under a multilateral international agreement specified in 35 U.S.C. 122(b)(2)(B)(i), must notify the Director of such filing not later than 45 days after the date of the filing of such foreign or international application. A failure of the applicant to provide such notice within the prescribed period shall result in the application being regarded as abandoned, unless it is shown to the satisfaction of the Director that the delay in submitting the notice was unintentional.**

**UTILITY PATENT APPLICATION TRANSMITTAL**  
**(Small Entity)**

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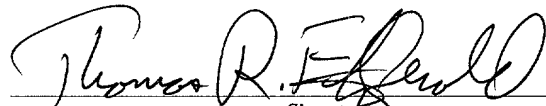
**Fee Calculation and Transmittal**

**CLAIMS AS FILED**

For	#Filed	#Allowed	#Extra	Rate	Fee
Total Claims	50	- 20 =	30	x \$9.00	\$270.00
Indep. Claims	2	- 3 =	0	x \$40.00	\$0.00
Multiple Dependent Claims (check if applicable) <input type="checkbox"/>					\$0.00
BASIC FEE					\$355.00
OTHER FEE (specify purpose) _____					\$0.00
TOTAL FILING FEE					\$625.00

- ☒ A check in the amount of **\$625.00** to cover the filing fee is enclosed.
- ☒ The Commissioner is hereby authorized to charge and credit Deposit Account No. **10-0223** as described below. A duplicate copy of this sheet is enclosed.
- ☐ Charge the amount of \_\_\_\_\_ as filing fee.
- ☒ Credit any overpayment.
- ☒ Charge any additional filing fees required under 37 C.F.R. 1.16 and 1.17.
- ☐ Charge the issue fee set in 37 C.F.R. 1.18 at the mailing of the Notice of Allowance, pursuant to 37 C.F.R. 1.311(b).

Dated: **October 12, 2000**

  
\_\_\_\_\_  
Signature  
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CC:

**CERTIFICATE OF MAILING BY "EXPRESS MAIL" (37 CFR 1.10)**Applicant(s): **A. Tanju Erdem**

Docket No.

**89589.113000**

Serial No.

**TBA**

Filing Date

**Herewith**

Examiner

**Unknown**

Group Art Unit

**Unknown**Invention: **METHOD FOR TRACKING MOTION OF A FACE**

I hereby certify that the following correspondence:

**Utility Patent Application Transmittal Letter (Small Entity) (4 pgs)***(Identify type of correspondence)*

is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 in an envelope addressed to: The Assistant Commissioner for Patents, Washington, D.C. 20231 on

**October 12, 2000***(Date)***Penny R. Turrell***(Typed or Printed Name of Person Mailing Correspondence)*  
*(Signature of Person Mailing Correspondence)***EL407177136US***("Express Mail" Mailing Label Number)***Note: Each paper must have its own certificate of mailing.**

**STATEMENT CLAIMING SMALL ENTITY STATUS  
(37 CFR 1.9(f) & 1.27(b))--INDEPENDENT INVENTOR**

Docket Number (Optional)  
89589.113000

Applicant, Patentee, or Identifier: A. Tanju Erdem

Application or Patent No.: TBA

Filed or Issued: Herewith

Title: METHOD FOR TRACKING MOTION OF A FACE

As a below named inventor, I hereby state that I qualify as an independent inventor as defined in 37 CFR 1.9(c) for purposes of paying reduced fees to the Patent and Trademark Office described in:

- ☒ the specification filed herewith with title as listed above.  
☐ the application identified above.  
☐ the patent identified above.

I have not assigned, granted, conveyed, or licensed, and am under no obligation under contract or law to assign, grant, convey, or license, any rights in the invention to any person who would not qualify as an independent inventor under 37 CFR 1.9(c) if that person had made the invention, or to any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a nonprofit organization under 37 CFR 1.9(e).

Each person, concern, or organization to which I have assigned, granted, conveyed, or licensed or am under an obligation under contract or law to assign, grant, convey, or license any rights in the invention is listed below:

- ☒ No such person, concern, or organization exists.  
☐ Each such person, concern, or organization is listed below.

Separate statements are required from each named person, concern, or organization having rights to the invention stating their status as small entities. (37 CFR 1.27)

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

A. Tanju Erdem

NAME OF INVENTOR

NAME OF INVENTOR

NAME OF INVENTOR



Signature of inventor

Signature of inventor

Signature of inventor

10/11/2000

Date

Date

Date

## METHOD FOR TRACKING MOTION OF A FACE

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### FIELD OF THE INVENTION

The present invention is related to the field of digital video processing and analysis, and more specifically, to a technique for tracking the three-dimensional (3-D)  
10 motion of a person's face from a sequence of two-dimensional (2-D) images of the person's face that are sequentially received in chronological order.

### BACKGROUND OF THE INVENTION

15 Tracking the 3-D motion of a face in a sequence of 2-D images of the face is an important problem with applications to facial animation, hands-free human-computer interaction environment, and lip-reading. Tracking the motion of the face involves tracking the 2-D positions of salient features on the face. The salient features could be in the form of (i) points, such as the corners of the mouth, the eye pupils, or external  
20 markers placed on the face; (ii) lines, such as the hair-line, the boundary of the lips, and the boundary of eyebrows; and (iii) regions, such as the eyes, the nose, and the mouth.

The salient features can also be synthetically created by placing markers on the face. Tracking of salient features is generally accomplished by detecting and matching a  
25 plurality of salient features of the face in a sequence of 2-D images of the face. The problem of detecting and matching the salient features is made difficult by variations in illumination, occlusion of the features, poor video quality, and the real-time constraint on the computer processing of the 2-D images.

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### SUMMARY OF THE INVENTION

The present invention provides an improvement designed to satisfy the aforementioned needs. Particularly, the present invention is directed to a computer program product for tracking the motion of a person's face from a chronologically  
35 ordered sequence of images of the person's face for the purpose of animating a 3-D model of the same or another person's face, by performing the steps of: (a) receiving a sequence of 2-D images of a person's face; (b) tracking the salient features of the

# METHOD FOR TRACKING MOTION OF A FACE

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person's face in the 2-D images; and (c) obtaining the 3-D global and local motion of the face from the tracked 2-D location of the salient features.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the course of the following detailed description, reference will be made to the attached drawings in which:

FIG. 1 is a perspective view of a computer system for implementing the present invention;

FIG. 2 is a first flowchart for the method of the present invention;

FIG. 3 is a second flowchart for the method of the present invention;

FIG. 4 is a diagram illustrating the method of placing markers on a person's face;

FIG. 5 is a diagram further illustrating the method of placing markers on a person's face;

FIG. 6a is a diagram illustrating the method of calculating the calibration parameter of the camera with a target object;

FIG. 6b is a diagram illustrating the image of the target object captured by the camera;

FIG. 7 is a diagram illustrating the method of acquiring a plurality of neutral images of a person's face using the camera;

FIG. 8 is a diagram further illustrating the method of acquiring a plurality of action images of a person's face using the camera;

FIG. 9 is a first table illustrating the method of locating global and local markers on the person's face;

FIG. 10 is a second table illustrating the method of locating global and local markers on the person's face;

FIG. 11 is a table illustrating the method of determining the surface normals of the global markers;

FIG. 12 is a table illustrating the method of determining the surface normals and the motion planes of the local markers;

## DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. 1, there is illustrated a computer system 10 for implementing the present invention. The computer system 10 includes a microprocessor-based unit 12 for receiving and processing software programs and for performing other well known processing functions. The software programs are contained on a computer useable medium 14, typically a compact disk, and are input into the microprocessor based unit 12 via the compact disk player 16 electronically connected to the microprocessor-based unit 12. As an alternate to using the compact disk 14, programs could also be contained in an Internet server 18 and input into the microprocessor-based unit 12 via an Internet connection 20. A camera 22 is electronically connected to the microprocessor-based unit 12 to capture the 2-D images of a person's face. A display 24 is electronically connected to the microprocessor-based unit 12 for displaying the images and user related information associated with the software. A keyboard 26 is connected to the microprocessor based unit 12 for allowing a user to input information to the software. A mouse 28 is also connected to the microprocessor based unit 12 for selecting items on the display 24 or for entering 2-D position information to the software, as is well known in the art. As an alternate to using the mouse 28, a digital pen 30 and a digital pad 32 may be used for selecting items on the display 24 and entering position information to the software. The output of the computer system is either stored on a hard disk 34 connected to the microprocessor unit 12, or uploaded to the Internet server 18 via the Internet connection 20. Alternatively, the output of the computer system can be stored on another computer useable medium 14, typically a compact disk, via a compact disk writer 36. The below-described steps of the present invention are implemented on the computer system 10.

Referring to FIGS. 2 and 3, there are illustrated the ten steps of the present invention which are first succinctly outlined and later described in detail. The first five steps are the initialization steps of the invention. Briefly stated, the first five steps are as follows: (a) selecting or placing salient features on the person's face (Step 100); (b) calculating the calibration parameter of the camera (Step 110); (c) acquiring a plurality of images of the person's face using the camera (Step 120); (d) calculating the 3-D positions of the salient features (Step 130); and (e) determining the surface normals and motion planes for the salient features (Step 140). The second five steps are the tracking steps of

the invention. Briefly stated, the second five steps are as follows: (f) acquiring a chronologically ordered sequence of 2-D images of the person's face in action (Step 150); (g) locking onto the salient features (Step 160); (h) tracking the global and local motion of the face (Step 170); (i) determining tracking failure (Step 180); and (j) storing or transmitting the global and local motion values (Step 190).

#### A. Selecting or Placing Features On The Person's Face For Motion Tracking (Step 100)

Referring to FIGS. 3 and 4, in the first step 100, salient features are selected or placed on the person's face for tracking the global and local motion of the face. Salient features that can be selected for tracking the global motion are the hairline, the corners of the eyes, the nostrils, and contours of the ears. Salient features that can be selected for tracking the local motion are the eyebrows, eyelids, pupils, and the lips. Methods have been proposed in the prior art for using the aforementioned salient features to track the global and local motion of the face. In a preferred embodiment of the present invention, salient features are designed and placed on the face rather than selected from what is naturally available on the face. It is important to note that placing salient features on the face allows for faster and more reliable motion tracking under adverse conditions for tracking, such as variations in illumination, poor video quality, and partial occlusion of the features.

Referring the FIG. 4, in a first preferred embodiment of the invention, circular markers are placed on a head-set that is worn by the person. The head-set may comprise a strap 206 for the skull, a strap 207 for the chin, and a strap 208 for the eyebrows. To achieve rotation invariance, two concentric circles are used to create the markers; one having twice the diameter of the other one, and the small one placed on top of the larger one. To achieve the highest contrast, the circles are painted in black and white. Thus, in the preferred embodiment, two types of markers are used: black-on-white 213 and white-on-black 214 markers. Those skilled in the art understand that other markers may be used, including and not limited to fluorescent dyes and contrasting paints.

Referring the FIG. 5, in a second preferred embodiment of the invention, circular markers are placed directly on the person's face. Markers are placed on the following ten locations on the person's face for tracking the global motion of the face, henceforth they are referred to as the global markers: right-ear-base 251, left-ear-base 252, right-temple

253, left-temple 254, right-outer-forehead 255, left-outer-forehead 256, right-central-forehead 257, left-central-forehead 258, nose-base 259, and nose-tip 260. Markers are placed on the following six locations on the person's face for tracking the local motion of the face, henceforth they are referred to as the local markers: right-lip-corner 261, left-lip-corner 262, upper-lip-center 263, lower-lip-center 264, right-central-eyebrow 265, and left-central-eyebrow 266.

## B. Calculating The Calibration Parameter Of The Camera (Step 110)

Referring to FIGS. 6a and 6b, in the second step 110, a perspective image of a target object is captured with the camera with the target object being placed at approximately the same distance from the camera as the person's face. The method of the present invention uses the perspective image of the target object to calculate a camera parameter that is used in the subsequent steps, hereinafter referred to as the  $E$  parameter. It is instructive to note at this point that the  $E$  parameter has a non-negative value and it is a measure of the amount of perspective deformation caused by the camera. A zero value indicates no perspective deformation and the larger the value of the  $E$  parameter the more the perspective deformation caused by the camera.

Still referring to FIGS. 6a and 6b, in a preferred embodiment of the invention, a square-shaped object 211 is employed as the target object and the value of the  $E$  parameter of the camera is calculated as follows: First, the four corners of the quadrilateral 212 are either automatically detected or manually marked by a user on the image 213 of the object captured by the camera. Let  $(x_n, y_n)$ ,  $n = 1, 2, 3, 4$ , represent 2-D the coordinates of the four corners of the object expressed in units of pixels with respect to the center 214 of the image 213. Letting  $(X_n, Y_n, Z_n)$ ,  $n = 1, 2, 3, 4$ , represent the corresponding 3-D coordinates of the corners of the object in 3-D in units of meters with respect to the location 215 of the camera, the relationship between the 2-D and 3-D coordinates are mathematically expressed as follows:

$$x_n = \frac{X_n}{Z_n} FD,$$

$$y_n = \frac{Y_n}{Z_n} FD,$$

where  $F$  denotes the focal length of camera in meters, and  $D$  denotes the meter to pixel conversion factor. For the purpose of present invention, it is necessary to find only the value of the product  $FD$ . In the present invention, we refer to the inverse of this product as the  $E$  parameter, hence in mathematical terms

$$E = \frac{1}{FD}.$$

We also take advantage of the fact that the target object is square shaped and planar, hence letting  $\alpha I$  denote the 3-D vector from  $(X_1, Y_1, Z_1)$  to  $(X_2, Y_2, Z_2)$  and  $\alpha J$  denote the 3-D vector from  $(X_1, Y_1, Z_1)$  to  $(X_4, Y_4, Z_4)$ , where  $I$  and  $J$  are orthonormal vectors and  $\alpha$  is the size of the square, we have the following mathematical expressions for the 3-D positions of the corners of the square object:

$$(X_2, Y_2, Z_2) = (X_1, Y_1, Z_1) + \alpha I,$$

$$(X_3, Y_3, Z_3) = (X_1, Y_1, Z_1) + \alpha I + \alpha J,$$

$$(X_4, Y_4, Z_4) = (X_1, Y_1, Z_1) + \alpha J.$$

It is well known to anyone having knowledge in the field of 3-D geometry that the pair of 3-D orthonormal vectors  $(I, J)$  are specified uniquely with 3 real numbers. Thus, on the right hand side of the above equation set there is a total of 7 unknown real numbers defining the square object: 3 in  $(I, J)$ , 3 in  $(X_1, Y_1, Z_1)$ , and the size of the square  $\alpha$ . Hence, including the  $E$  parameter, the following set of equations

$$x_n = \frac{1}{E} \frac{X_n}{Z_n},$$

$$y_n = \frac{1}{E} \frac{Y_n}{Z_n},$$

has a total of 8 unknown real numbers on the right hand side, and 8 measured quantities, namely  $(x_n, y_n)$ ,  $n = 1, 2, 3, 4$ , on the left hand side, resulting in a unique solution for the unknown real numbers in terms of the measured quantities. It is well known to anyone knowledgeable in the field of algebra how to obtain the value of the  $E$  parameter from the above equation set given only the measured quantities  $(x_n, y_n)$ ,  $n = 1, 2, 3, 4$ .

### C. Acquiring A Plurality Of Images Of A Person's Face Using The Camera (Step 120)

Referring to FIG. 2, the method of acquiring a plurality of images of a person's face using the camera comprises the steps of (1) acquiring neutral images of the face (Step 121); and (2) acquiring action images of the face (Step 122). In the following, a detailed description of these steps is given.

5

#### C1. Acquiring Neutral Images Of The Face (Step 121)

Referring to FIGS. 2 and 7, in the third step 120, a plurality of 2-D images of the person's face in the same neutral state are captured with the camera from different  
10 directions. The neutral state for the face means that all face muscles are relaxed, eyes are normally open, mouth is closed and lips are in contact. These images are subsequently used to obtain the neutral 3-D positions of the salient features of the face, hence, hereinafter they are referred to as the neutral images. The camera directions to capture  
15 neutral images are selected so that the majority of salient features are visible in all images. The face is not required to be at the same distance from the camera in all the neutral images.

Still referring to FIG. 7, in a preferred embodiment of the present invention, markers are placed on the person's face as described in Step 100, and fifteen camera directions selected for obtaining the neutral images. In order to obtain the neutral images,  
20 the camera remains fixed and the person rotates his/her head to realize the following fifteen different directions: front 221, forehead 222, chin 223, angled-right 224, angled-right-tilted-down 225, angled-right-tilted-up 226, angled-left 227, angled-left-tilted-down 228, angled-left-tilted-up 229, full-right-profile 230, full-right-profile-tilted-down 231, full-right-profile-tilted-up 232, full-left-profile 233, full-left-profile-tilted-down 234, and  
25 full-left-profile-tilted-up 235.

#### C2. Acquiring Action Images Of The Face (Step 122)

Referring to FIGS. 2 and 8, in the third step 120, a plurality of 2-D images of the  
30 person's face in action states are captured with the camera from different directions. The action states for the face include faces with a smiling mouth, a yawning mouth, raised eyebrows, etc. These images are subsequently used to obtain the 3-D position of the local salient features when the face is in action states, hence, hereinafter they are referred to as the action images. The camera directions to capture the action images are selected so that

the majority of salient features are visible in all images. The face is not required to be at the same distance from the camera in all the action images.

Still referring to FIG. 8, in a preferred embodiment of the present invention, markers are placed on the person's face as described in Step 100 and five facial action states and two camera directions for each action are selected. The facial action states are as follows: smiling mouth, yawning mouth, kissing mouth, raised eyebrows, and squeezed eyebrows. The camera directions are front and right. In order to obtain the action images, the camera remains fixed and the person rotates his/her head while his/her face assumes an action state to capture the following ten different images: front-yawning-mouth 241, right-angled-yawning-mouth 242, front-smiling-mouth 243, right-angled-smiling-mouth 244, front-kissing-mouth 245, right-angled-kissing-mouth 246, front-raised-eyebrows 247, right-angled-raised-eyebrows 248, front-squeezed-eyebrows- 249, right-angled-squeezed-eyebrows 250.

#### D. Calculating The Neutral 3-D Positions Of The Salient Features (Step 130)

Referring to FIG. 2, the method calculating the neutral 3-D positions of the salient features comprises the steps of (1) locating the global and local salient features in the neutral and action images (Step 131); (2) calculating the 3-D positions of the global and local salient features for the neutral face (Step 132); and (3) calculating the 3-D positions of the local salient features for the action faces (Step 133). In the following, a detailed description of these steps is given.

##### D1. Locating The Global And Local Salient Features In The Neutral And Action Images (Step 131)

The salient features are automatically or manually located on the acquired images. It is important to note that not all of the salient features may be visible in all neutral and action images and some salient features may not be in their neutral position in some action images. Thus, in the present invention, the location of only the visible salient features and salient features that are in their neutral position are automatically or manually located in each neutral and action image.

In a preferred embodiment of the invention, markers that are placed on the face are used as the salient features as described in Step 100. These markers are manually

located in the neutral images that are indicated with an X in the table in FIG. 9, and are manually located in action images that are indicated with an X in FIG. 10. The markers are assumed as invisible in those neutral images that are not indicated with an X in the table in FIG. 9. The markers are not in their neutral position in those action images that are not indicated with an X in the table in FIG. 10. In operation, the computer program prompts the user to manually locate only the visible markers and markers that are in their neutral position in each image.

## D2. Calculating The 3-D Positions Of The Global And Local Salient Features For The Neutral Face (Step 132)

Given the 2-D locations of the salient features in the neutral images where they are visible, and the value of the  $E$  parameter of the camera obtained in Step 110, the 3-D positions of the salient features of the person's face are calculated using a modified version of the method in "Shape and Motion from Image Streams under Orthography: A Factorization Method" by Carlo Tomasi and Takeo Kanade, *International Journal of Computer Vision*, vol. 9, no. 2, pp. 137-154, 1992. In a preferred embodiment of the present invention, global and local markers placed on the person's face as described in Step 100 are used as the salient features. In the following, first, a general mathematical analysis of 2-D image projections of 3-D marker positions is given. Next, the method of "Shape and Motion from Image Streams under Orthography" is reviewed. Then, the proposed modification to the method of "Factorization of Shape and Motion" is presented.

Without loss of generality, assume that the coordinate axes of the camera system are the unit vectors  $\hat{i} = (1,0,0)$ ,  $\hat{j} = (0,1,0)$ , and  $\hat{k} = (0,0,1)$ . Hence, the image plane passes at  $(0,0,-F)$  and is perpendicular to  $\hat{k}$ . Let  $N$  denote the number of global markers and  $P_n$ ,  $n = 1, \dots, N$ , denote the coordinates of the global markers with respect to the origin  $(0,0,0)$  of the camera system. Likewise, let  $M$  denote the number of local markers and  $Q_n$ ,  $n = 1, \dots, M$ , denote the coordinates of the local markers with respect to the origin  $(0,0,0)$  of the camera system. Clearly, as the person's face is moved, the coordinates, of all the markers are changed. It is therefore more appropriate to use a local coordinate system for the face to represent the coordinates of the markers. Let the unit



vectors  $\tilde{i}$ ,  $\tilde{j}$ , and  $\tilde{k}$  denote the coordinate axes for an arbitrary local coordinate system for the face. The origin  $C_0$  of the local coordinate system is defined to be the centroid of the markers and is given by

$$C_0 = \frac{1}{N+M} \left( \sum_{n=1}^N P_n + \sum_{n=1}^M Q_n \right).$$

Furthermore, let  $A_n$ ,  $n=1, \dots, N$ , denote the coordinates of the global markers and let  $B_n$ ,  $n=1, \dots, M$ , denote the coordinates of the local markers with respect to the origin of the local coordinate system. Thus, as the person's face is moved, the origin of the local coordinate system is changed but the local coordinates of the markers always remain fixed.

In order to relate the global coordinates  $P_n$ ,  $n=1, \dots, N$ , and  $Q_n$ ,  $n=1, \dots, M$ , to the local coordinates  $A_n$ ,  $n=1, \dots, N$ , and  $B_n$ ,  $n=1, \dots, M$ , define the unit vectors  $\hat{I} = (\tilde{i}_x, \tilde{j}_x, \tilde{k}_x)$ ,  $\hat{J} = (\tilde{i}_y, \tilde{j}_y, \tilde{k}_y)$ , and  $\hat{K} = (\tilde{i}_z, \tilde{j}_z, \tilde{k}_z)$ , where the subscripts  $x$ ,  $y$ , and  $z$ , denote the coordinates of the respective vectors along the axes  $\hat{i}$ ,  $\hat{j}$ , and  $\hat{k}$  of the global coordinate system. Then, the relationship between the global coordinates and the local coordinates of the feature points is given by

$$\begin{aligned} P_{n,x} &= C_{0,x} + A_n \bullet \hat{I}, & Q_{n,x} &= C_{0,x} + B_n \bullet \hat{I} \\ P_{n,y} &= C_{0,y} + A_n \bullet \hat{J}, & Q_{n,y} &= C_{0,y} + B_n \bullet \hat{J} \quad \text{and} \\ P_{n,z} &= C_{0,z} + A_n \bullet \hat{K}, & Q_{n,z} &= C_{0,z} + B_n \bullet \hat{K} \end{aligned}$$

where  $\bullet$  denotes the inner product of two vectors. Finally, the 2-D coordinates of the feature points projected on the image plane are expressed as

$$\begin{aligned} p_{n,x} &= \frac{1}{E} \frac{C_{0,x} + A_n \bullet \hat{I}}{C_{0,z} + A_n \bullet \hat{K}}, & q_{n,x} &= \frac{1}{E} \frac{C_{0,x} + B_n \bullet \hat{I}}{C_{0,z} + B_n \bullet \hat{K}} \quad \text{and} \\ p_{n,y} &= \frac{1}{E} \frac{C_{0,y} + A_n \bullet \hat{J}}{C_{0,z} + A_n \bullet \hat{K}}, & q_{n,y} &= \frac{1}{E} \frac{C_{0,y} + B_n \bullet \hat{J}}{C_{0,z} + B_n \bullet \hat{K}}, \end{aligned}$$

where the quantities on the left hand side are in units of pixels while the quantities of the right hand side, except the  $E$  parameter and the unit vectors, are in units of meters. The above equations can be rewritten with all quantities in units of pixels as follows:

$$p_{n,x} = \frac{c_{0,x} + S_n \bullet \hat{I}}{\lambda + ES_n \bullet \hat{K}}, \quad q_{n,x} = \frac{c_{0,x} + L_n \bullet \hat{I}}{\lambda + EL_n \bullet \hat{K}} \quad \text{and}$$

$$p_{n,y} = \frac{c_{0,y} + S_n \bullet \hat{J}}{\lambda + ES_n \bullet \hat{K}}, \quad q_{n,y} = \frac{c_{0,y} + L_n \bullet \hat{J}}{\lambda + EL_n \bullet \hat{K}}$$

where

$$c_{0,x} = \frac{C_{0,x}}{EW}, \quad c_{0,y} = \frac{C_{0,y}}{EW}, \quad \lambda = \frac{C_{0,z}}{W}, \quad S_n = \frac{A_n}{EW}, \quad \text{and} \quad L_n = \frac{B_n}{EW},$$

5

where  $W$  is some constant in units of meters that will be defined shortly.

It is now time to write the above equations for all neutral images. Suppose the number of neutral images is  $F$ , then the general equations for 2-D projections of markers are

10

$$p_{n,x}^f = \frac{c_{0,x}^f + S_n \bullet \hat{I}^f}{\lambda^f + ES_n \bullet \hat{K}^f}, \quad q_{n,x}^f = \frac{c_{0,x}^f + L_n \bullet \hat{I}^f}{\lambda^f + EL_n \bullet \hat{K}^f} \quad \text{and}$$

$$p_{n,y}^f = \frac{c_{0,y}^f + S_n \bullet \hat{J}^f}{\lambda^f + ES_n \bullet \hat{K}^f}, \quad q_{n,y}^f = \frac{c_{0,y}^f + L_n \bullet \hat{J}^f}{\lambda^f + EL_n \bullet \hat{K}^f},$$

where  $f = 1, \dots, F$ , denotes the image number. Note that all quantities in the above equations vary with the image number, except for the local coordinates of the markers and of course the  $E$  parameter. The parameter  $W$  has the same value for all  $f = 1, \dots, F$ , otherwise its value is arbitrary.

15

The method of ‘‘Shape and Motion from Image Streams under Orthography’’ assumes a special form of 2-D projection, namely, the orthographic projection. In orthographic projection, it is assumed that  $C_{0,z}$  is the same for all images,  $W = C_{0,z}$ , and  $W \gg 1$ . Thus, the above general equations reduce to the following form in the case of orthographic projections:

20

$$p_{n,x}^f = c_{0,x}^f + S_n \bullet \hat{I}^f, \quad q_{n,x}^f = c_{0,x}^f + L_n \bullet \hat{I}^f \quad \text{and}$$

$$p_{n,y}^f = c_{0,y}^f + S_n \bullet \hat{J}^f, \quad q_{n,y}^f = c_{0,y}^f + L_n \bullet \hat{J}^f.$$

25

The quantities on the left hand side are measured quantities while the quantities on the right hand side are unknown quantities. The method of “Factorization of Shape and Motion” solves the above equations for the 3-D local coordinates  $S_n$  and  $L_n$  of the global and local markers, respectively, the orientation vectors  $\hat{I}^f$  and  $\hat{J}^f$ , and the 2-D position  $(c^f_{0,x}, c^f_{0,y})$  of the centroid of the markers in all images in terms of the 2-D projected positions  $(p^f_{n,x}, p^f_{n,y})$  and  $(q^f_{n,x}, q^f_{n,y})$  of the global and local markers, respectively, in all images.

In the following, a modification to the method of “Shape and Motion from Image Streams under Orthography” is presented in order to solve the general 2-D projection equations given above for the 3-D local coordinates  $S_n$  and  $L_n$  of the markers, the orientation vectors  $\hat{I}^f$  and  $\hat{J}^f$ , the 2-D position  $(c^f_{0,x}, c^f_{0,y})$  of the centroid of the markers, and the distance ratio  $\lambda^f$  in all images in terms of the 2-D projected positions  $(p^f_{n,x}, p^f_{n,y})$  and  $(q^f_{n,x}, q^f_{n,y})$  of the markers in all images. Note that the third orientation vector  $\hat{K}^f$  is uniquely defined by the first two orientation vectors  $\hat{I}^f$  and  $\hat{J}^f$  simply as

$$\hat{K}^f = \hat{I}^f \times \hat{J}^f,$$

where  $\times$  denotes the vector outer product. The proposed modification method is an iterative procedure whose steps are as given below:

1. Use the method of “Shape and Motion from Image Streams under Orthography” that employs the orthographic projection equations to calculate  $S_n$  for  $n = 1, \dots, N$ ,  $L_n$  for  $n = 1, \dots, M$ ,  $\hat{I}^f$ ,  $\hat{J}^f$  and  $(c^f_{0,x}, c^f_{0,y})$  for  $f = 1, \dots, F$ , given the 2-D measurements  $(p^f_{n,x}, p^f_{n,y})$ ,  $(q^f_{n,x}, q^f_{n,y})$  and the visibility information of the markers. Let  $\hat{K}^f = \hat{I}^f \times \hat{J}^f$ .
2. Calculate  $\lambda^f$  for  $f = 1, \dots, F$ , using the general projection equations as

$$\lambda^f = \frac{1}{\sum_{n=1}^N \|(p_{n,x}^f, p_{n,y}^f)\| + \sum_{n=1}^M \|(q_{n,x}^f, q_{n,y}^f)\|} \cdot \left( \sum_{n=1}^N \left( \|(c_{0,x}^f + S_n \bullet \hat{I}^f, c_{0,y}^f + S_n \bullet \hat{J}^f)\| - \|(p_{n,x}^f, p_{n,y}^f)\| ES_n \bullet \hat{K}^f \right) + \sum_{n=1}^M \left( \|(c_{0,x}^f + L_n \bullet \hat{I}^f, c_{0,y}^f + L_n \bullet \hat{J}^f)\| - \|(q_{n,x}^f, q_{n,y}^f)\| EL_n \bullet \hat{K}^f \right) \right)$$

3. Modify the 2-D measurements  $(p_{n,x}^f, p_{n,y}^f)$ ,  $n = 1, \dots, N$ , and  $(q_{n,x}^f, q_{n,y}^f)$ ,  $n = 1, \dots, M$ , for  $f = 1, \dots, F$ , using the calculated values in Steps 1 and 2 as

$$p_{n,x}^f \leftarrow p_{n,x}^f (\lambda^f + ES_n \bullet \hat{K}^f), \quad q_{n,x}^f \leftarrow q_{n,x}^f (\lambda^f + EL_n \bullet \hat{K}^f) \text{ and} \\ p_{n,y}^f \leftarrow p_{n,y}^f (\lambda^f + ES_n \bullet \hat{K}^f), \quad q_{n,y}^f \leftarrow q_{n,y}^f (\lambda^f + EL_n \bullet \hat{K}^f).$$

4. Repeat Steps 1, 2, and 3 until a predetermined number of iterations has been reached, or the following average measurement of matching error

$$\varepsilon = \frac{1}{V} \left( \sum_{f=1}^F \left( \sum_{n=1}^N \left\| p_{n,x}^f - \frac{c_{0,x}^f + S_n \bullet \hat{I}^f}{\lambda^f + ES_n \bullet \hat{K}^f}, \quad p_{n,y}^f - \frac{c_{0,y}^f + S_n \bullet \hat{J}^f}{\lambda^f + ES_n \bullet \hat{K}^f} \right\|^2 \right) + \sum_{n=1}^M \left\| q_{n,x}^f - \frac{c_{0,x}^f + L_n \bullet \hat{I}^f}{\lambda^f + EL_n \bullet \hat{K}^f}, \quad q_{n,y}^f - \frac{c_{0,y}^f + L_n \bullet \hat{J}^f}{\lambda^f + EL_n \bullet \hat{K}^f} \right\|^2 \right)^{\frac{1}{2}}$$

goes below a predetermined threshold, where the summation is only over the visible markers in each image, the quantity  $V$  denotes the total number of visible markers in all images, and  $(p_{n,x}^f, p_{n,y}^f)$  and  $(q_{n,x}^f, q_{n,y}^f)$  are the original 2-D measurements. In a preferred embodiment of the invention, the number of iterations is selected to be 50 and the threshold is selected to be 1 pixel.

The 3-D positions  $S_n$ ,  $n = 1, \dots, N$ , and  $L_n$ ,  $n = 1, \dots, M$ , of the global and local markers are globally translated and rotated so that they correspond to a frontal-looking face. In a preferred embodiment of the invention, the 3-D positions of the global markers

right-ear-base **251**, left-ear-base **252**, nose-base **259**, and nose-tip **260** are used to globally translate and rotate the the 3-D positions of the global and local markers so that they correspond to a frontal-looking face. Let  $r_1$  and  $r_2$  denote the 3-D positions of the right-ear-base **251** and left-ear-base **252**, respectively;  $f$  denote the 3-D position of the nose-base **259**; and  $b$  denote the 3-D position of the nose-tip **260**. Then, the following procedure is used to globally translate the positions of the markers:

1. Define the following vector

$$c = \frac{1}{2}(r_1 + r_2).$$

2. Subtract  $c$  from each  $S_n$  and  $L_n$ , i.e.,

$$S_n \leftarrow S_n - c \quad \text{and} \quad L_n \leftarrow L_n - c$$

so that the center of the feature points is shifted to the mid-point of the right-ear-base **251** and the left-ear-base **252**.

Following the global translation of the markers, in a preferred embodiment of the invention, the following procedure is used to globally rotate the marker positions so that they correspond to a frontal-looking face:

1. Define the following three vectors

$$u = r_2 - r_1, \quad v = f - b, \quad \text{and} \quad w = f - \frac{1}{2}(r_1 + r_2).$$

2. Use the Gram-Schmidt orthonormalization procedure to convert the vectors  $u$ ,  $v$ , and  $w$  into an orthonormal set of vectors. As a result,  $u$  simply will be normalized; only the component of  $v$  that is perpendicular to  $u$  will be retained and subsequently normalized; and only the component of  $w$  that is perpendicular to both  $u$  and the modified  $v$  will be retained and subsequently normalized.

3. Form the  $3 \times 3$  rotation matrix  $T$  so that the columns of  $T$  consist of the orthonormalized vectors  $u$ ,  $v$ ,  $w$ , i.e.,

$$T = \begin{bmatrix} u & v & w \end{bmatrix}.$$

4. Finally, left-multiply each  $S_n$  and  $L_n$  with  $T$ , i.e.,

$$S_n \leftarrow TS_n \quad \text{and} \quad L_n \leftarrow TL_n.$$

### D3. Calculating The 3-D Positions Of The Local Salient Features For The Action Faces (Step 133)

Given the 3-D positions of the salient features obtained in Step 132, the 2-D measurements of the salient features obtained in Step 131, and the value of the  $E$  parameter of the camera obtained in Step 110, the method of calculating the 3-D positions of the local salient features for the action faces is disclosed in the following. In a preferred embodiment of the present invention, global and local markers placed on the person's face as described in Step 100 are used as the salient features. First, the position and orientation of the person's face in the action images are calculated using the 3-D positions  $S_n$  of the global markers and the 2-D measurements  $(p_{n,x}^f, p_{n,y}^f)$  of the global markers in the action images. Then, the 3-D positions  $L_n^{(i)}$  of the local markers in the action states are calculated using the position and orientation of the person's face in the action images and the 2-D measurements  $(q_{n,x}^f, q_{n,y}^f)$  of the local markers in the action images.

It facilitates understanding to note that the 3-D position of the face in an image  $f$  is described by the centroid  $(c_{0,x}^f, c_{0,y}^f)$  of the markers and the camera-distance-ratio  $\lambda^f$  of the face in that image. Likewise, the 3-D orientation of the face in an image  $f$  is described by the vectors  $\hat{I}^f$  and  $\hat{J}^f$  in that image. The 3-D position and orientation parameters  $(c_{0,x}^f, c_{0,y}^f)$ ,  $\lambda^f$ ,  $\hat{I}^f$  and  $\hat{J}^f$  in the action images are calculated using the following steps:

1. Use the motion-only-estimation method of “Factorization of Shape and Motion” that employs the orthographic projection equations to calculate  $\hat{I}^f$ ,  $\hat{J}^f$  and  $(c^f_{0,x}, c^f_{0,y})$  in the action images given the 2-D measurements  $(p^f_{n,x}, p^f_{n,y})$  and the visibility information of the global markers in the action images, and the 3-D positions  $S_n$  of the markers calculated in Step 132.  
Let  $\hat{K}^f = \hat{I}^f \times \hat{J}^f$ .

2. Calculate  $\lambda^f$  using the general projection equations as

$$\lambda^f = \frac{1}{\sum_{n=1}^N \|(p^f_{n,x}, p^f_{n,y})\|} \sum_{n=1}^N \left( \|(c^f_{0,x} + S_n \bullet \hat{I}^f, c^f_{0,y} + S_n \bullet \hat{J}^f)\| - \|(p^f_{n,x}, p^f_{n,y})\| ES_n \bullet \hat{K}^f \right)$$

3. Modify the 2-D measurements  $(p^f_{n,x}, p^f_{n,y})$  for  $n=1, \dots, N$ , using the calculated values in Step 1 and 2 as

$$p^f_{n,x} \leftarrow p^f_{n,x} (\lambda^f + ES_n \bullet \hat{K}^f), \text{ and}$$

$$p^f_{n,y} \leftarrow p^f_{n,y} (\lambda^f + ES_n \bullet \hat{K}^f).$$

4. Repeat Steps 1, 2, and 3 until a predetermined number of iterations has been reached, or the following average measurement of matching error

$$\varepsilon^f = \left( \frac{1}{U} \sum_{n=1}^N \left\| \left( p^f_{n,x} - \frac{c^f_{0,x} + S_n \bullet \hat{I}^f}{\lambda^f + ES_n \bullet \hat{K}^f}, p^f_{n,y} - \frac{c^f_{0,y} + S_n \bullet \hat{J}^f}{\lambda^f + ES_n \bullet \hat{K}^f} \right) \right\|^2 \right)^{\frac{1}{2}}$$

for the image goes below a predetermined threshold, where the summation is only over the visible points in the image, the quantity  $U$  denotes the total number of visible points in the image, and  $(p^f_{n,x}, p^f_{n,y})$  are the original 2-D measurements. In a preferred embodiment of the invention, the number of iterations is selected to be 50 and the threshold is selected to be 1 pixel.

The 3-D positions  $L_n$  of the local markers for the action faces are then calculated using the following steps:

1. Use the shape-only-estimation method of “Factorization of Shape and Motion” that employs the orthographic projection equations to calculate the 3-D positions  $L_n^{(i)}$  of the local markers in action state  $i$  given the position  $(c_{0,x}^f, c_{0,y}^f)$  and orientation  $\hat{I}^f, \hat{J}^f$  of the face, the measurements  $(q_{n,x}^f, q_{n,y}^f)$ , and the visibility information of the local markers in the 2-D images of the action state  $i$ . Referring to FIG. 8, in a preferred embodiment of the invention, there are 5 action states where action state  $i=1$  corresponds to a yawning mouth **241** and **242**, action state  $i=2$  corresponds to a smiling mouth **243** and **244**, action state  $i=3$  corresponds to a kissing mouth **245** and **246**, action state  $i=4$  corresponds to raised eyebrows **247** and **248**, and action state  $i=5$  corresponds to squeezed eyebrows **249** and **250**.
2. Modify the 2-D measurements  $(q_{n,x}^f, q_{n,y}^f)$  for  $n=1, \dots, M$ , and for each action state  $i$ , using the calculated values in Step 1 as

$$q_{n,x}^f \leftarrow q_{n,x}^f (\lambda^f + EL_n^{(i)} \bullet \hat{K}^f), \text{ and}$$

$$q_{n,y}^f \leftarrow q_{n,y}^f (\lambda^f + EL_n^{(i)} \bullet \hat{K}^f).$$

3. Repeat Steps 1 and 2 until a predetermined number of iterations has been reached, or the following average measurement of matching error

$$\varepsilon^f = \left( \frac{1}{U} \sum_{n=1}^M \left\| \left( q_{n,x}^f - \frac{c_{0,x}^f + L_n^{(i)} \bullet \hat{I}^f}{\lambda^f + EL_n^{(i)} \bullet \hat{K}^f}, q_{n,y}^f - \frac{c_{0,y}^f + L_n^{(i)} \bullet \hat{J}^f}{\lambda^f + EL_n^{(i)} \bullet \hat{K}^f} \right) \right\|^2 \right)^{\frac{1}{2}}$$

for the image goes below a predetermined threshold, where the summation is only over the visible points in the image, the quantity  $U$  denotes the total number of visible points in the image, and  $(q_{n,x}^f, q_{n,y}^f)$  are the original 2-D



measurements. In a preferred embodiment of the invention, the number of iterations is selected to be 50 and the threshold is selected to be 1 pixel.

#### E. Determining The Surface Normals And Motion Planes For The Salient Features (Step 140)

Referring to FIG. 2, in the fifth step, a surface normal is defined for each marker. The surface normals are used during the tracking process to determine if a marker is visible in a 2-D image. The surface normal for a marker is defined to be the vector perpendicular to the surface of the face at the location of the marker. In a preferred embodiment of the invention, the vectors given in the table in FIG. 11 are defined as the surface normals for the global markers. The surface normals for local markers are given in FIG. 12. It should be noted that the surface normals given in the tables in FIGS. 11 and 12 are not necessarily normalized. They can be normalized to so that they all have unit length. The normalized surface normals for the global and local markers are denoted by  $\Omega_n$  for  $n = 1, \dots, N$ , and  $\Psi_n$  for  $n = 1, \dots, M$ , respectively. The surface normals for the markers are used later in Step 170 to determine the visibilities of the markers in a 2-D image.

#### F. Receiving A Chronologically Ordered Sequence Of 2-D Images Of The Person's Face In Action (Step 150)

Referring to FIG. 3, in the sixth step 150, a video of the face of the person in action is received. The 2-D images of the video are processed to track the salient features on the face and to calculate the global and local motion of the face in the order they are received.

#### G. Locking Onto The Selected Features On The Person's Face (Step 160)

Referring to FIG. 3, in the seventh step 160, a locking method is used to start tracking the salient features of the face. The locking method is used at the very beginning of the tracking process or whenever the tracking is lost, as described in Step 190. initial

images of the video are used to lock the tracking process onto the salient features on the face.

In a preferred embodiment of the invention, cross-like signs are displayed on top of the 2-D image to be associated with the markers on the face. The locations of the signs are determined by projecting the 3-D positions of the markers obtained in Step 132 assuming a frontal orientation of the face. To achieve locking, the person looks directly at the camera so as to produce a frontal view positioned at the center of the image. The person moves his/her face back and forth and also rotates his/her face if necessary until all the markers on his/her face are positioned at approximately the same location as the associated signs on the display. The method of the present invention considers the locations of the cross-like signs as the predicted locations for the features and uses the method of Step 173 to calculate the current motion in the 2-D image. If the calculated motion corresponds to a frontal orientation at the center of the display, then the method of the present invention considers a lock onto the features has been achieved.

#### H. Tracking The 3-D Global And Local Motion Of The Face In Each 2-D Image (Step 170)

Referring to FIG. 4, the method finding the 3-D global and local motion of the face in each 2-D image comprises the steps of (1) predicting the global motion (Step 171); (2) detecting the global salient features (Step 172); (3) estimating the global motion (Step 173); (4) predicting the local motion (Step 174); (5) detecting the local salient features (Step 175); and (6) estimating the local motion (Step 176). In the following, a detailed description of these steps is given.

##### H1. Predicting The Locations of Global Salient Features (Step 171)

The global motion of the face in a 2-D image is defined to be the 3-D orientation and position of the face in the 2-D image. Referring to FIG. 4, in the eighth step, the global motion of the face in a 2-D image that is currently processed is predicted from the motion of the face in the previously processed 2-D images. In a preferred embodiment of the invention, the calculated position and orientation of the face in the immediate

previous 2-D image is used as the prediction for the global motion in the current 2-D image. Thus, the predicted locations  $(\tilde{p}_{n,x}, \tilde{p}_{n,y})$  for  $n = 1, \dots, N$ , of the global markers in the current 2-D image are calculated using

$$\tilde{p}_{n,x} = \frac{\tilde{c}_{0,x} + S_n \bullet \tilde{I}}{\tilde{\lambda} + ES_n \bullet \tilde{K}}, \quad \tilde{p}_{n,y} = \frac{\tilde{c}_{0,y} + S_n \bullet \tilde{J}}{\tilde{\lambda} + ES_n \bullet \tilde{K}},$$

where,  $(\tilde{c}_{0,x}, \tilde{c}_{0,y})$ ,  $\tilde{\lambda}$ ,  $\tilde{I}$  and  $\tilde{J}$  denote the global motion parameters found in the previous 2-D image, and  $\tilde{K} = \tilde{I} \times \tilde{J}$ .

## H2. Detecting The Global Salient Features (Step 172)

The method of detecting the global markers in the current 2-D image is comprised of the following steps:

1. Determine the visibility indices of the global markers: Calculate the visibility index  $\omega_n$  for each global marker:

$$\omega_n = \tilde{K} \bullet \Omega_n.$$

It is important to note that the closer the value of the index  $\omega_n$  to 1, the more visible is the global marker.

2. Design correlation filters for detecting the markers: It is important to note that the two concentric circles that form a global marker will appear like two concentric ellipses in the current 2-D image. The minor axis of the ellipse will be in the direction of the vector  $(\tilde{I} \bullet \Omega_n, \tilde{J} \bullet \Omega_n)$ , and the length of the minor axis will be  $|\tilde{K} \bullet \Omega_n| R \sigma_n$  while the length of the major axis will be  $R \sigma_n$ , where  $R$  is the diameter of the outer circle in units of pixel and  $\sigma_n$  is given by

$$\sigma_n = \frac{1}{\lambda + ES_n \bullet \tilde{K}}.$$

Thus, in order to detect global marker  $n$  in the current 2-D image, a 2-D correlation filter is designed that has the support given by the outer ellipse and having the value of 1 inside the inner ellipse and the value of 0 elsewhere. Let the coefficients of the 2-D correlation filter for the global marker  $n$  be given by  $c_n(x, y)$ .

3. Detect the global markers: If the visibility index  $\omega_n$  of global marker  $n$  is larger than a visibility threshold, then apply the correlation filter  $c_n(x, y)$  designed in Step 2 for the global marker  $n$  in a  $W \times W$  square region centered at the predicted location  $(\tilde{p}_{n,x}, \tilde{p}_{n,y})$  of the global marker  $n$  to obtain a correlation surface  $f_n(i, j)$  for the global marker  $n$ :

$$f_n(i, j) = \sum c_n(x, y) \cdot I(x + i + \tilde{p}_{n,x}, y + j + \tilde{p}_{n,y}), \quad -\frac{W}{2} < i, j < \frac{W}{2},$$

where the summation is over the support of the correlation filter  $c_n(x, y)$  and  $I(x, y)$  denotes the intensity distribution of the 2-D image with the center of the image being at  $(0,0)$ . In a preferred embodiment of the invention, the visibility threshold is selected as 0.25 and the size  $W$  of the square region is selected as 20 pixels. Find the location  $(i_n^*, j_n^*)$  where the correlation surface  $f_n(i, j)$  achieves its peak value. Then, the image location  $(x_n, y_n) = (i_n^* + \tilde{p}_{n,x}, j_n^* + \tilde{p}_{n,y})$  is assigned as the detected location of the global marker  $n$  in the current 2-D image. Let  $Q_n$  denote this peak value.

4. Eliminate superfluous and multiple detected locations: If the distance between any two detected locations is less than a distance threshold, but larger than zero, then discard the detected location that has a smaller peak value. On the other hand, if the exact same location is detected for more than one global marker, then assign the detected location only to the global marker that has the

largest visibility index. In a preferred embodiment of the invention, the distance threshold is selected to be 1 pixel. All global markers that are not assigned a valid detected location are assumed invisible for the purpose of estimating the global motion that is done in the following Step 173.

5

### H3. Estimating The Global Motion (Step 173)

Suppose, at the end of Step 172, there are  $L$  valid detected locations assigned to  $L$  global markers. The 3-D orientation  $\hat{I}$  and  $\hat{J}$ , and the 3-D position  $(c_{0,x}, c_{0,y})$ ,  $\lambda$ , of the face in the current 2-D image are then calculated from these  $L$  detected locations using the following steps:

10

1. Use the motion-only-estimation method of “Factorization of Shape and Motion” that employs the orthographic projection equations to calculate  $\hat{I}$ ,  $\hat{J}$  and  $(c_{0,x}, c_{0,y})$  given the 2-D locations  $(x_n, y_n)$  and the visibility information of the global markers in the action images, and the 3-D positions  $S_n$  of the markers calculated in Step 132. Let  $\hat{K} = \hat{I} \times \hat{J}$ .

15

2. Calculate  $\lambda$  using the general projection equations as

20

$$\lambda = \frac{1}{\sum_n \|(x_n, y_n)\|} \sum_n \left( \|(c_{0,x} + S_n \bullet \hat{I}, c_{0,y} + S_n \bullet \hat{J})\| - \|(x_n, y_n)\| ES_n \bullet \hat{K} \right),$$

where the summation is only over the visible global markers.

3. Modify the 2-D locations  $(x_n, y_n)$  using the calculated values in Step 1 and 2

25

as

$$x_n \leftarrow x_n (\lambda + ES_n \bullet \hat{K}), \text{ and}$$

$$y_n \leftarrow y_n (\lambda + ES_n \bullet \hat{K}).$$

4. Repeat Steps 1, 2, and 3 until a predetermined number of iterations has been reached, or the following average measurement of matching error

$$\varepsilon = \left( \frac{1}{L} \sum_n \left\| \left( x_n - \frac{c_{0,x} + S_n \bullet \hat{I}}{\lambda + ES_n \bullet \hat{K}}, y_n - \frac{c_{0,y} + S_n \bullet \hat{J}}{\lambda + ES_n \bullet \hat{K}} \right) \right\|^2 \right)^{\frac{1}{2}}$$

goes below a predetermined threshold, where the summation is only over the visible global markers. In a preferred embodiment of the invention, the number of iterations is selected to be 50 and the threshold is selected to be 1 pixel.

#### H4. Predicting The Locations of Local Salient Features (Step 174)

The local motion of the face in a 2-D image is defined through an action vector that represents the actions of the face in the 2-D image. In a preferred embodiment of the invention there are a total of 5 actions, hence the action vector has 5 components:

$$A = (A_{MY}, A_{MS}, A_{MK}, A_{ER}, A_{ES})$$

$A_{MY}$  being the amount of yawning-mouth action,  $A_{MS}$  being the amount of smiling-mouth action,  $A_{MK}$  being the amount of kissing-mouth action,  $A_{ER}$  being the amount of raised-eyebrows action, and  $A_{ES}$  being the amount of squeezed-eyebrows action. For example, an action vector  $A = (0.5, 0.0, 0.0, 1.0, 0.0)$  represents a half-yawning mouth and fully raised eyebrows.

As mentioned in Step 133, there are 5 action states. It facilitates understanding to give examples of action vectors for the action states. Action state  $i=1$  that corresponds to a yawning mouth has action vector  $A = (1.0, 0.0, 0.0, 0.0, 0.0)$  while action state  $i=5$  that corresponds to squeezed eyebrows has action vector  $A = (0.0, 0.0, 0.0, 0.0, 1.0)$ . The neutral state of the face is represented by the action vector  $A = (0.0, 0.0, 0.0, 0.0, 0.0)$ .

During the locking process explained in Step 160, the face is in the neutral state, hence the action vector is given by  $A = (0.0, 0.0, 0.0, 0.0, 0.0)$ . In any subsequent 2-D image

of the face, the action vector found for the previous image is used as the predicted action vector for the current image. Let  $\tilde{A}$  denote the predicted action vector for the current image. Let

$$\bar{L}_n = (L_n^{(1)} - L_n, L_n^{(2)} - L_n, L_n^{(3)} - L_n, L_n^{(4)} - L_n, L_n^{(5)} - L_n)$$

denote the action displacement vector for local marker  $n$ . Then, the predicted 3-D positions  $\tilde{L}_n$  of the local markers in the current image are calculated as follows:

$$\tilde{L}_n = \tilde{A} \bullet \bar{L}_n + L_n.$$

Finally, the predicted 2-D locations  $(\tilde{q}_{n,x}, \tilde{q}_{n,y})$  of the local markers in the current image are calculated using

$$\tilde{q}_{n,x} = \frac{\tilde{c}_{0,x} + \tilde{L}_n \bullet \tilde{I}}{\tilde{\lambda} + E\tilde{L}_n \bullet \tilde{K}}, \quad \tilde{q}_{n,y} = \frac{\tilde{c}_{0,y} + \tilde{L}_n \bullet \tilde{J}}{\tilde{\lambda} + E\tilde{L}_n \bullet \tilde{K}},$$

where,  $(\tilde{c}_{0,x}, \tilde{c}_{0,y})$ ,  $\tilde{\lambda}$ ,  $\tilde{I}$  and  $\tilde{J}$  denote the global motion parameters found in the previous 2-D image, and  $\tilde{K} = \tilde{I} \times \tilde{J}$ .

##### H5. Detecting The Local Salient Features (Step 175)

The method of detecting the global markers in the current 2-D image is comprised of the following steps:

1. Determine the visibility indices of the local markers: Calculate the visibility index  $\psi_n$  for each local marker:

$$\psi_n = \tilde{K} \bullet \Psi_n.$$

It is important to note that the closer the value of the index  $\psi_n$  to 1, the more visible is the local marker.

2. Design correlation filters for detecting the markers: It is important to note that the two concentric circles that form a local marker will appear like two

concentric ellipses in the current 2-D image. The minor axis of the ellipse will be in the direction of the vector  $(\tilde{I} \bullet \Psi_n, \tilde{J} \bullet \Psi_n)$ , and the length of the minor axis will be  $|\tilde{K} \bullet \Psi_n| R \mu_n$  while the length of the major axis will be  $R \mu_n$ , where  $R$  is the diameter of the outer circle in units of pixel and  $\mu_n$  is given by

$$\mu_n = \frac{1}{\lambda + E \tilde{L}_n \bullet \tilde{K}}.$$

Thus, in order to detect local marker  $n$  in the current 2-D image, a 2-D correlation filter is designed that has the support given by the outer ellipse and having the value of 0 inside the inner ellipse, the value of 1 in the outer ellipse, and the value of 0 elsewhere. Let the coefficients of the 2-D correlation filter for the local marker  $n$  be given by  $d_n(x, y)$ .

3. Detect the local markers: If the visibility index  $\psi_n$  of local marker  $n$  is larger than a visibility threshold, then apply the correlation filter  $d_n(x, y)$  designed in Step 2 for local marker  $n$  in a  $W \times W$  square region centered at the predicted location  $(\tilde{q}_{n,x}, \tilde{q}_{n,y})$  of local marker  $n$  to obtain a correlation surface  $h_n(i, j)$  for local marker  $n$ :

$$h_n(i, j) = \sum d_n(x, y) \cdot I(x + i + \tilde{q}_{n,x}, y + j + \tilde{q}_{n,y}), \quad -\frac{W}{2} < i, j < \frac{W}{2},$$

where the summation is over the support of the correlation filter  $d_n(x, y)$  and  $I(x, y)$  denotes the intensity distribution of the 2-D image with the center of the image being at (0,0). In a preferred embodiment of the invention, the visibility threshold is selected as 0.25 and the size  $W$  of the square region is selected as 20 pixels. Find the location  $(i_n^*, j_n^*)$  where the correlation surface  $h_n(i, j)$  achieves its peak value. Then, the image location



$(u_n, v_n) = (i_n^* + \tilde{q}_{n,x}, j_n^* + \tilde{q}_{n,y})$  is assigned as the detected location of the global marker  $n$  in the current 2-D image. Let  $Q_n$  denote this peak value.

4. Eliminate superfluous and multiple detected locations: If the distance between any two detected locations is less than a distance threshold, but larger than zero, then discard the detected location that has a smaller peak value. On the other hand, if the exact same location is detected for more than one local marker, then assign the detected location only to the local marker that has the largest visibility index. In a preferred embodiment of the invention, the distance threshold is selected to be 1 pixel. All local markers that are not assigned a valid detected location are assumed invisible for the purpose of estimating the local motion that is done in the following Step 176.

#### H6. Estimating The Local Motion (Step 176)

The local motion of the face is represented by an action vector as described in Step 174. In a first preferred embodiment of the invention, the action vector for the current image is calculated using the following steps:

1. Calculate the 2-D displacements of the local markers: The 2-D locations  $(q_{n,x}, q_{n,y})$  of the local markers corresponding to the neutral face are calculated using the global motion found for the current image as:

$$q_{n,x} = \frac{\tilde{c}_{0,x} + L_n \bullet \hat{I}}{\tilde{\lambda} + EL_n \bullet \hat{K}}, \quad q_{n,y} = \frac{\tilde{c}_{0,y} + L_n \bullet \hat{J}}{\tilde{\lambda} + EL_n \bullet \hat{K}}.$$

The 2-D displacements  $(d_{n,x}, d_{n,y})$  are then calculated as

$$d_{n,x} = u_n - q_{n,x}, \quad d_{n,y} = v_n - q_{n,y}.$$

2. Modify the 2-D displacements so that they correspond to orthographic projection:

$$d_{n,x} \leftarrow d_{n,x} (\lambda + EL_n \bullet \hat{K}), \quad \text{and}$$

$$d_{n,y} \leftarrow d_{n,y} (\lambda + EL_n \bullet \hat{K}).$$

3. Calculate the 3-D displacements of the local markers: The 3-D displacements of the local markers are calculated from the 2-D displacements of the local markers, the 2-D motion planes of the local markers, and the global motion of the face in the current image. The 2-D motion plane of a local marker passes from the neutral 3-D position of the local marker and approximates the motion space of local marker with a plane. Two basis vectors are used to define each motion plane. Let  $B_{1,n}$  and  $B_{2,n}$  denote the basis vectors 1 and 2 for the local marker  $n$ . The basis vectors for the motion planes of the local markers are given in FIG. 12. The 3-D displacements of the local markers are then calculated as follows. Form the matrix  $M_n$  for each local marker

$$M_n = \begin{bmatrix} B_{1,n} \cdot \hat{I} & B_{2,n} \cdot \hat{I} \\ B_{1,n} \cdot \hat{J} & B_{2,n} \cdot \hat{J} \end{bmatrix}$$

and solve for the coefficients  $\alpha_{1,n}$  and  $\alpha_{2,n}$  in

$$\begin{bmatrix} d_{n,x} \\ d_{n,y} \end{bmatrix} = M_n \begin{bmatrix} \alpha_{1,n} \\ \alpha_{2,n} \end{bmatrix}.$$

Then, the 3-D displacements  $U_n$  are given by

$$U_n = \alpha_{1,n} \cdot B_{1,n} + \alpha_{2,n} \cdot B_{2,n}.$$

Once the 3-D moved positions of the markers are calculated they can be modified so as to satisfy the motion symmetries of the face. Examples of motion symmetries of the face are as follows: the right and the left eyebrows move simultaneously and by the same amount, and the right and the left corners of the mouth move simultaneously and by the same amount.

The calculated 3-D displacements of the markers can be further modified to enforce motion dependencies of the face. An example of a motion dependency of the face is as follows: as the corners of the mouth move towards the center of the mouth, the centers of the top and bottom lips move forward.

The calculated 3-D displacements of the markers can be still further modified by filtering. The filtering of the calculated 3-D displacements of the face smooth out the jitter in the calculated 3-D positions that can be caused by errors in the detected 2-D positions of the markers.

4. Finally, the action vector  $(a_1, \dots, a_M)$  for the current image is calculated by solving the following equation for  $(a_1, \dots, a_M)$  in the least-squares sense:

$$\begin{bmatrix} U_1 \\ \vdots \\ U_M \end{bmatrix} = \begin{bmatrix} \bar{L}_1 \\ \vdots \\ \bar{L}_M \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ \vdots \\ a_M \end{bmatrix}.$$

5

In a second preferred embodiment of the invention, the action vector for the current image is calculated using the following steps:

1. Calculate the 2-D locations  $(q_{n,x}, q_{n,y})$  of the local markers corresponding to the neutral face using the global motion found for the current image as:

$$q_{n,x} = \frac{\tilde{c}_{0,x} + L_n \bullet \hat{I}}{\tilde{\lambda} + EL_n \bullet \hat{K}}, \quad q_{n,y} = \frac{\tilde{c}_{0,y} + L_n \bullet \hat{J}}{\tilde{\lambda} + EL_n \bullet \hat{K}}.$$

Still referring to FIGS. 5 and 9, local marker  $n=1$  corresponds to Right-lip-corner **261**,  $n=2$  corresponds to Left-lip-corner **262**,  $n=3$  corresponds to Upper-lip-center **263**,  $n=4$  corresponds to Lower-lip-center **264**,  $n=5$  corresponds to Right-central-eyebrow **265**, and  $n=6$  corresponds to Left-central-eyebrow **266**.

Also calculate the 2-D location  $(p_{9,x}, p_{9,y})$  of the global marker  $n=9$  Nose-base **259** using the global motion found for the current image as:

$$p_{n,x} = \frac{\tilde{c}_{0,x} + S_n \bullet \hat{I}}{\tilde{\lambda} + ES_n \bullet \hat{K}}, \quad p_{n,y} = \frac{\tilde{c}_{0,y} + S_n \bullet \hat{J}}{\tilde{\lambda} + ES_n \bullet \hat{K}},$$

where  $n$  is set to 9 for the global marker Nose-base **259**.

2. Calculate the 2-D locations  $(q^{(i)}_{n,x}, q^{(i)}_{n,y})$  of the local markers corresponding to the action states of the face using the global motion found for the current image as:

$$q^{(i)}_{n,x} = \frac{\tilde{c}_{0,x} + L^{(i)}_n \bullet \hat{I}}{\tilde{\lambda} + EL^{(i)}_n \bullet \hat{K}}, \quad q^{(i)}_{n,y} = \frac{\tilde{c}_{0,y} + L^{(i)}_n \bullet \hat{J}}{\tilde{\lambda} + EL^{(i)}_n \bullet \hat{K}},$$

where  $i$  is the index of the facial action. Still referring to FIG. 8, in a preferred embodiment of the invention, there are 5 action states where action state  $i=1$  corresponds to a yawning mouth **241** and **242**, action state  $i=2$  corresponds to a smiling mouth **243** and **244**, action state  $i=3$  corresponds to a kissing mouth **245** and **246**, action state  $i=4$  corresponds to raised eyebrows **247** and **248**, and action state  $i=5$  corresponds to squeezed eyebrows **249** and **250**.

3. Determine the fractional displacements  $f^{(1)}$ ,  $f^{(2)}$ , and  $f^{(3)}$  for yawning-mouth, smiling-mouth, and kissing mouth actions, respectively, as follows. The fractional displacement  $f^{(1)}$  is determined based on the distance between the Upper-lip-center **263** and Lower-lip-center **264** in the yawning-mouth action state  $i=1$  of the face, and in the neutral state of the face, and the distance between the detected positions of those markers:

$$f^{(1)} = \frac{\frac{\|u_3 - u_4\|}{\|v_3 - v_4\|} - \frac{\|q_{3,x} - q_{4,x}\|}{\|q_{3,y} - q_{4,y}\|}}{\frac{\|q^{(1)}_{3,x} - q^{(1)}_{4,x}\|}{\|q^{(1)}_{3,y} - q^{(1)}_{4,y}\|} - \frac{\|q_{3,x} - q_{4,x}\|}{\|q_{3,y} - q_{4,y}\|}}.$$

The fractional displacement  $f^{(2)}$  is determined based on the distance between the Right-lip-corner **261** and Left-lip-corner **262** in the smiling-mouth action state  $i=2$  of the face, and in the neutral state of the face, and the distance between the detected positions of those markers:

$$f^{(2)} = \frac{\frac{\|u_1 - u_2\|}{\|v_1 - v_2\|} - \frac{\|q_{1,x} - q_{2,x}\|}{\|q_{1,y} - q_{2,y}\|}}{\frac{\|q^{(2)}_{1,x} - q^{(2)}_{2,x}\|}{\|q^{(2)}_{1,y} - q^{(2)}_{2,y}\|} - \frac{\|q_{1,x} - q_{2,x}\|}{\|q_{1,y} - q_{2,y}\|}}.$$

Finally, the fractional displacement  $f^{(3)}$  is determined based on the distance between the Right-lip-corner **261** and Left-lip-corner **262** in the kissing-mouth action state  $i=3$  of the face, and in the neutral state of the face, and the distance between the detected positions of those markers:

$$f^{(3)} = \frac{\left\| \begin{matrix} u_1 - u_2 \\ v_1 - v_2 \end{matrix} \right\| - \left\| \begin{matrix} q_{1,x} - q_{2,x} \\ q_{1,y} - q_{2,y} \end{matrix} \right\|}{\left\| \begin{matrix} q^{(3)}_{1,x} - q^{(3)}_{2,x} \\ q^{(3)}_{1,y} - q^{(3)}_{2,y} \end{matrix} \right\| - \left\| \begin{matrix} q_{1,x} - q_{2,x} \\ q_{1,y} - q_{2,y} \end{matrix} \right\|}.$$

Then, clip the values of the fractional displacements  $f^{(1)}$ ,  $f^{(2)}$ , and  $f^{(3)}$  to the range  $[0,1]$  and use the following method to determine the first three components of the action vector  $(a_1, \dots, a_5)$ :

- If  $f^{(3)} > f^{(2)}$  and  $f^{(3)} > f^{(1)}$  then  $a_1 = 0$ ,  $a_2 = 0$ , and  $a_3 = f^{(3)}$
- Otherwise, if  $f^{(2)} > f^{(3)}$  and  $f^{(2)} > f^{(1)}$  then  $a_1 = 0$ ,  $a_2 = f^{(2)}$ , and  $a_3 = 0$ .
- Otherwise,  $a_1 = f^{(1)}$ ,  $a_2 = 0$ , and  $a_3 = 0$ .

4. Determine the fractional displacements  $f^{(4)}$  and  $f^{(5)}$  for raised-eyebrows and squeezed-eyebrows, respectively, as follows. The fractional displacement  $f^{(4)}$  is determined based on the distance between the local markers Right-central-eyebrow **265**, Left-central-eyebrow **266**, and the global marker Nose-base **259** in the raised-eyebrows action state  $i=4$  of the face, and in the neutral state of the face, and the distance between the detected positions of those markers:

$$f^{(4)} = \frac{\left\| \begin{matrix} (u_5 + u_6)/2 - x_9 \\ (v_5 + v_6)/2 - y_9 \end{matrix} \right\| - \left\| \begin{matrix} (q_{5,x} + q_{6,x})/2 - p_{9,x} \\ (q_{5,y} + q_{6,y})/2 - p_{9,y} \end{matrix} \right\|}{\left\| \begin{matrix} (q^{(4)}_{5,x} + q^{(4)}_{6,x})/2 - p_{9,x} \\ (q^{(4)}_{5,y} + q^{(4)}_{6,y})/2 - p_{9,y} \end{matrix} \right\| - \left\| \begin{matrix} (q_{5,x} + q_{6,x})/2 - p_{9,x} \\ (q_{5,y} + q_{6,y})/2 - p_{9,y} \end{matrix} \right\|}.$$

The fractional displacement  $f^{(5)}$  is determined based on the distance between the Right-central-eyebrow **265** and Left-central-eyebrow **266** in the squeezed-eyebrows action state  $i=5$  of the face, and in the neutral state of the face, and the distance between the detected positions of those markers:

$$f^{(5)} = \frac{\left\| \begin{matrix} u_5 - u_6 \\ v_5 - v_6 \end{matrix} \right\| - \left\| \begin{matrix} q_{5,x} - q_{6,x} \\ q_{5,y} - q_{6,y} \end{matrix} \right\|}{\left\| \begin{matrix} q^{(5)}_{5,x} - q^{(5)}_{6,x} \\ q^{(5)}_{5,y} - q^{(5)}_{6,y} \end{matrix} \right\| - \left\| \begin{matrix} q_{5,x} - q_{6,x} \\ q_{5,y} - q_{6,y} \end{matrix} \right\|}.$$

Then, clip the values of the fractional displacements  $f^{(4)}$  and  $f^{(5)}$  to the range  $[0,1]$  and use the following method to determine the last two components of the action vector  $(a_1, \dots, a_5)$ :

- If  $f^{(5)} > f^{(4)}$  then  $a_4 = 0$  and  $a_5 = f^{(5)}$
- Otherwise,  $a_4 = f^{(4)}$  and  $a_5 = 0$ .

#### I. Determining If There Is A Tracking Failure (Step 180)

If there is a large change in the global motion of the face in the current image as compared to the global motion of the face in the previous image, then it is concluded that there is a tracking failure. In a preferred embodiment of the invention, the following equation is used to calculate the change  $\delta$  in the global motion in the current image with respect to the previous image:

$$\delta = \left( (c^f_{0,x} - c^{f-1}_{0,x})^2 + (c^f_{0,y} - c^{f-1}_{0,y})^2 + (\lambda^f - \lambda^{f-1})^2 / E^2 \right)^{\frac{1}{2}} + 100 \cdot \left( 1 - |\hat{I}^f \bullet \hat{I}^{f-1}| + 1 - |\hat{J}^f \bullet \hat{J}^{f-1}| + 1 - |\hat{K}^f \bullet \hat{K}^{f-1}| \right).$$

In a preferred embodiment of the invention, if  $\delta$  is greater than 50 then it is concluded that there is a motion failure.

#### J. Storing Or Transmitting Global And Local Facial Motion Values (Step 190)

The calculated global motion of the face is in terms of the 3-D orientation vectors  $\hat{I}^f$  and  $\hat{J}^f$ , the 2-D centroid  $(c^f_{0,x}, c^f_{0,y})$  of the face, and the camera-distance ratio  $\lambda^f$ . The superscript  $f$  denotes the chronological order number for the motion values. The following equations are used to convert the calculated global motion parameters into a

more direct representation that uses a 3-D rotation matrix  $R^f$  and a 3-D position vector  $T^f$ :

$$R^f = \begin{bmatrix} \hat{I}_x^f & \hat{I}_y^f & \hat{I}_z^f \\ \hat{J}_x^f & \hat{J}_y^f & \hat{J}_z^f \\ \hat{K}_x^f & \hat{K}_y^f & \hat{K}_z^f \end{bmatrix}, \quad T^f = \begin{bmatrix} c_{0,x}^f \\ c_{0,y}^f \\ (\lambda^f - 1)/E \end{bmatrix},$$

where  $\hat{K}^f = \hat{I}^f \times \hat{J}^f$ , and the subscripts  $x, y$ , and  $z$ , denote the  $x$ -,  $y$ -, and  $z$ - components of a vector.

Thus, only the global motion parameters  $R^f$  and  $T^f$  are stored or transmitted to describe the global motion of the face. Likewise, only the action vectors  $A^f$  are stored or transmitted to describe the motion of the face.

What is claimed is:

1. A method for tracking motion of a face comprising the steps of:  
selecting salient features of the face for motion tracking; and  
tracking motion of the salient features of the face.
2. The method of claim 1 further comprising:  
acquiring a plurality of initial 2-D images of the face;  
calculating 3-D locations of the salient features; and  
determining a surface normal for each salient features.
3. The method of claim 1 further comprising:  
receiving a chronologically ordered sequence of 2-D images of the face in action; and  
locking onto the salient features.
4. The method of claim 1 further comprising:  
tracking 3-D global motion of the face in each image; and  
tracking 3-D local motion of the face in each image.
5. The method of claim 1 wherein the step of selecting comprises fixing markers to the  
face and the step of tracking comprises tracking the motion of the markers.
6. The method of claim 5 wherein a first set of markers identifies global motion and a  
second set of markers identifies local motion of the face.
7. The method of claim 4 wherein the step of tracking the 3-D global motion comprises  
the steps of:  
predicting the location of global salient features in a 2-D image;  
detecting global salient features in the 2-D image; and  
estimating the 3-D global motion of the face in the 2-D image.
8. The method of claim 7 wherein the step of estimating comprises calculating the  
position and shape of the face to conform to the 3-D locations and the detected  
locations of the global markers under a perspective projection model.



9. The method of claim 4 wherein the step of tracking the 3-D local motion comprises the steps of:

predicting the location of local salient features;

detecting local salient features; and

estimating the 3-D local motion of the face.

10. The method of claim 9 wherein the step of estimating comprises:

finding 3-D locations of local markers to conform to the detected 2-D locations of the local markers; and

calculating an action vector representing the weights of facial actions in the 2-D image conforming to the found 3-D locations of local markers and the 3-D locations of the local markers for the neutral and the action states under a perspective projection model.

11. A method for tracking motion of a face comprising the steps of:

determining the calibration parameter of a camera;

selecting salient features on the face for motion tracking;

acquiring a plurality of initial 2-D images of the face;

calculating 3-D locations of the salient features in accordance with the calibration parameter of the camera;

determining a surface normal for each salient features;

receiving a chronologically ordered sequence of 2-D images of the face in action;

tracking motion of the face in each 2-D image; and

storing or transmitting tracked motion of the face.

12. The method of claim 11 further comprising the steps of:

locking onto the salient features; and

detecting loss of lock and hence the need for re-locking onto the salient features.

13. The method of claim 11 wherein the step of tracking comprises the steps of:

tracking the 3-D global motion of the face in each image; and

tracking the 3-D local motion of the face in each image.

14. The method of claim 11 comprising the further step of repeating the locking and tracking steps after the detecting step.

15. The method of claim 11 wherein the step of selecting comprises recognizing salient facial features and the step of tracking comprises tracking the motion of the salient facial features.

16. The method of claim 11 wherein the step of selecting comprises fixing markers to the face and the step of tracking comprises tracking the motion of the markers.

17. The method of claim 16 wherein a first set of markers identifies global motion and a second set of markers identifies local motion of the face.

18. The method of claim 17 wherein the markers comprise at least two colors.

19. The method of claim 18 wherein the two colors are contrasting.

20. The method of claim 19 wherein the colors are black and white.

21. The method of claim 16 wherein the markers comprise two concentric circles of different colors.

22. The method of claim 21 wherein the outer circle has a diameter at least twice the diameter of the inner circle.

23. The method of claim 11 wherein the step of selecting comprises wearing a head-set with markers.

24. The method of claim 23 wherein the head-set comprises a strap for a chin.

25. The method of claim 23 wherein the head-set comprises a strap for eyebrows.

26. The method of claim 23 wherein the head-set comprises at least one strap for a skull.

27. The method of claim 11 wherein the acquired 2-D images include at least two views of the face with markers in a neutral state at different orientations;

28. The method of claim 27 wherein the two views are orthogonal.

5

29. The method of claim 11 wherein the acquired 2-D images comprise front, forehead, chin, angled-right, angled-right-tilted-up, angled-right-tilted-down, angled-left, angled-left-tilted-up, angled-left-tilted-down, full-right-profile, full-right-profile-tilted-up, full-right-profile-tilted-down, full-left-profile, full-left-profile-tilted-up, and full-left-profile-tilted-down views of the face with markers in the neutral state.

10

30. The method of claim 11 wherein the acquired 2-D images comprise front, forehead, chin, full-right-profile, and full-left-profile views of the face with markers in the neutral state.

15

31. The method of claim 1 wherein the acquired 2-D images include a plurality of views of the face with markers in at least one action state.

32. The method of claim 31 wherein the action states of the face comprise smiling lips, kissing lips, yawning lips, raised eyebrows, and squeezed eyebrows.

20

33. The method of claim 31 wherein the acquired 2-D images of the face in an action state include at least two views at different orientations.

25

34. The method of claim 33 wherein the two views are front and angled-right.

35. The method of claim 11 wherein the step of selecting comprises fixing markers to the face and the step of calculating comprises calculating the 3-D locations of the markers placed on the face.

30

36. The method of claim 35 wherein the step of calculating the 3-D locations of the markers comprises the steps of:  
calculating the 3-D locations of the global and local markers in the neutral state; and  
calculating the 3-D locations of the local markers in each action state;

37. The method of claim 36 wherein the step of calculating the 3-D locations of the global and local markers in the neutral state comprises the steps of:  
calculating the 3-D locations of the markers to conform to their 2-D locations in the  
5 2-D images of the face in the neutral state under an orthographic projection model;  
calculating relative distances of the face to the camera in the 2-D images to conform  
to the 2-D locations of the markers and their calculated 3-D locations under a  
perspective projection model;  
modifying the 2-D locations of the markers to conform to the calculated relative  
10 distances and the 3-D locations under a perspective projection model;  
recalculating the 3-D locations of the markers to conform to their modified 2-D  
locations under an orthographic projection model;  
repeating the steps of calculating the relative distances, modifying the 2-D locations,  
and recalculating the 3-D locations to satisfy a convergence requirement; and  
15 translating and rotating the 3-D locations so that they correspond to a frontal-looking  
face.

38. The method of claim 36 wherein the step of calculating the 3-D locations of the local  
markers in each action state comprises the steps of:  
20 estimating the orientation and position of the face in each 2-D image of the action  
state to conform to the 3-D and 2-D locations of the global markers under a  
perspective projection model; and  
calculating the 3-D locations of the local markers to conform to the estimated  
orientation and position of the face and the 2-D locations of the local markers under a  
25 perspective projection model;

39. The method of claim 13 wherein the step of tracking the 3-D global motion comprises  
the steps of:  
predicting the location of global salient features in a 2-D image;  
30 detecting global salient features in the 2-D image; and  
estimating the 3-D global motion of the face in the 2-D image.

40. The method of claim 39 wherein the step of predicting comprises calculating 2-D  
locations of the global salient features under a perspective projection model using the

position and orientation of the face in a previous 2-D image, and the step of detecting comprise detecting the global markers.

41. The method of claim 40 wherein detecting the global markers comprises:

determining visibility indices of global markers;  
designing correlation filters for the global markers;  
detecting the global markers by applying elliptical correlation filters in a neighborhood of the global markers; and  
eliminating superfluous and multiple detected locations.

42. The method of claim 39 wherein the step of estimating comprises calculating the position and shape of the face to conform to the 3-D locations and the detected locations of the global markers under a perspective projection model.

43. The method of claim 13 wherein the step of tracking the 3-D local motion comprises the steps of:

predicting the location of local salient features;  
detecting local salient features; and  
estimating the 3-D local motion of the face.

44. The method of claim 43 wherein the local markers are placed on eyebrows and lips.

45. The method of claim 44 wherein the locations of the local markers comprise proximate ends of the eyebrows, corners of the lips, and the upper and lower centers of each lip.

46. The method of claim 43 wherein the step of predicting the locations of local markers comprises calculating the locations of the local markers using the position, orientation, and action values of the face in a previous 2-D image and the step of detecting comprise detecting the global markers.

47. The method of claim 44 wherein detecting the local markers comprise:

determining visibility indices of local markers;  
designing correlation filters for the local markers;

detecting the local markers by applying elliptical correlation filters in a neighborhood of the local markers; and  
eliminating superfluous and multiple detected locations.

48. The method of claim 43 wherein the step of estimating comprises:

finding 3-D locations of local markers to conform to the detected 2-D locations of the local markers;  
calculating an action vector representing the weights of facial actions in the 2-D image conforming to the found 3-D locations of local markers and the 3-D locations of the local markers for the neutral and the action states under a perspective projection model.

49. The method of claim 48 wherein the step of calculating an action vector comprises the steps of :

calculating the difference between the 2-D locations of the local markers detected in an image and the 2-D locations of the same markers corresponding to the neutral face;  
modifying the difference to conform to the orthographic projection;  
calculating the 3-D displacements of the local markers with respect to their location in the neutral face; and  
calculating the amount of facial actions conforming to the 3-D displacements of the local markers.

50. The method of claim 48 wherein the step of calculating an action vector comprises the steps of :

calculating the 2-D locations of the local markers corresponding to the neutral face using the global motion found for the current image;  
calculating the 2-D locations of the local markers corresponding to the action faces using the global motion found for the current image;  
calculating the distance between the detected locations, the distance between the neutral locations, and the distance between the action locations of the markers at the right and left corners of the lips;  
calculating the distance between the detected locations, the distance between the neutral locations, and the distance between the action locations of the markers at the upper and lower center of lips;

calculating the distance between the detected locations, the distance between the neutral locations, and the distance between the action locations of the markers at the proximate ends of the eyebrows;

determining the fractional displacements of the local markers for the lips area and for the eyebrows area; and

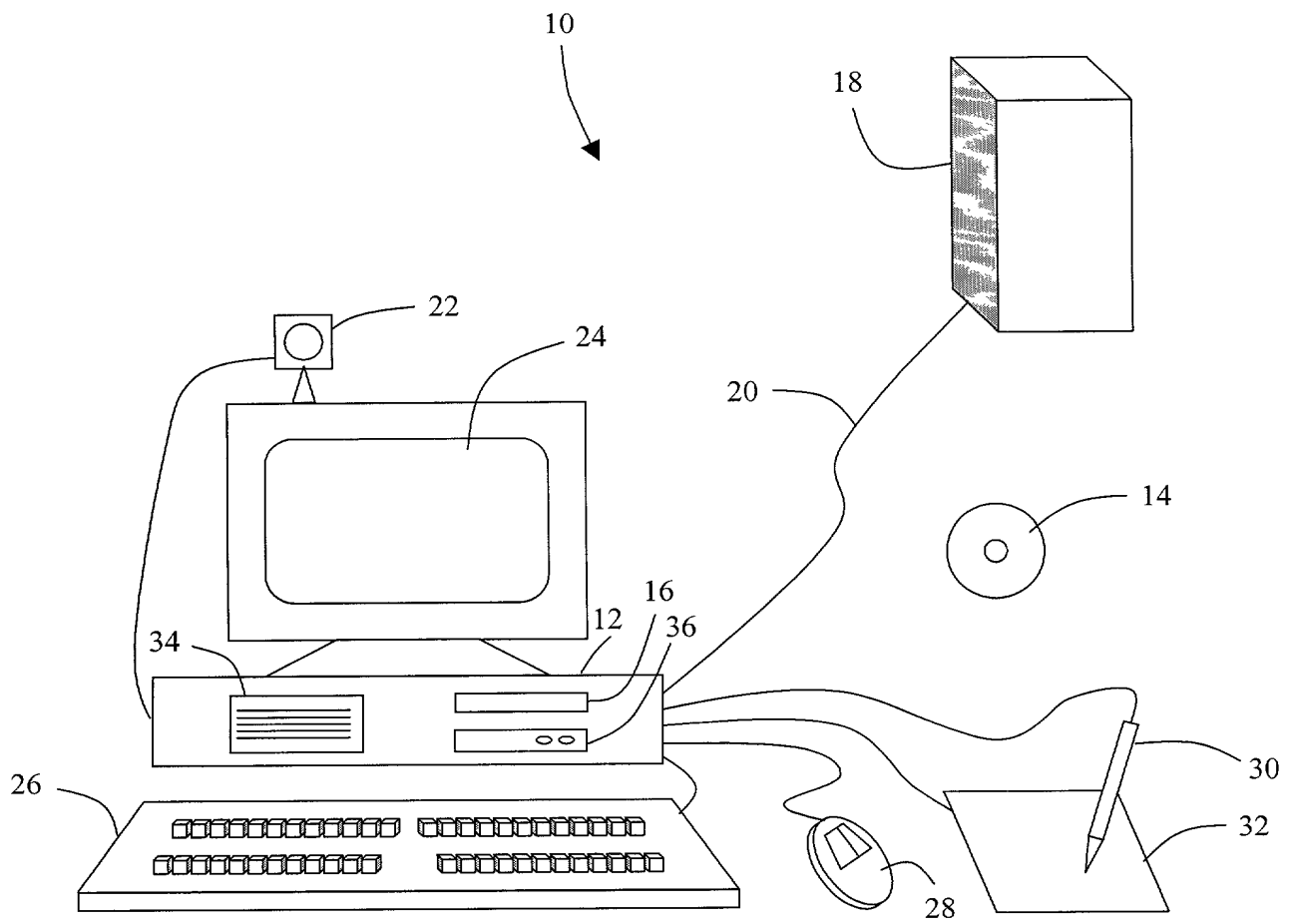
determining action mode and amount for the lips area and for the eyebrows area based on the fractional displacements of the local markers.

## ABSTRACT

5 A method for tracking the motion of a person's face for the purpose of animating  
a 3-D face model of the same or another person is disclosed. The 3-D face model carries  
both the geometry (shape) and the texture (color) characteristics of the person's face. The  
shape of the face model is represented via a 3-D triangular mesh (geometry mesh), while  
the texture of the face model is represented via a 2-D composite image (texture image).  
10 Both the global motion and the local motion of the person's face are tracked. Global  
motion of the face involves the rotation and the translation of the face in 3-D. Local  
motion of the face involves the 3-D motion of the lips, eyebrows, etc., caused by speech  
and facial expressions. The 2-D positions of salient features of the person's face and/or  
markers placed on the person's face are automatically tracked in a time-sequence of 2-D  
15 images of the face. Global and local motion of the face are separately calculated using the  
tracked 2-D positions of the salient features or markers. Global motion is represented in a  
2-D image by rotation and position vectors while local motion is represented by an action  
vector that specifies the amount of facial actions such as smiling-mouth, raised-eyebrows,  
etc.

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**FIG. 1**

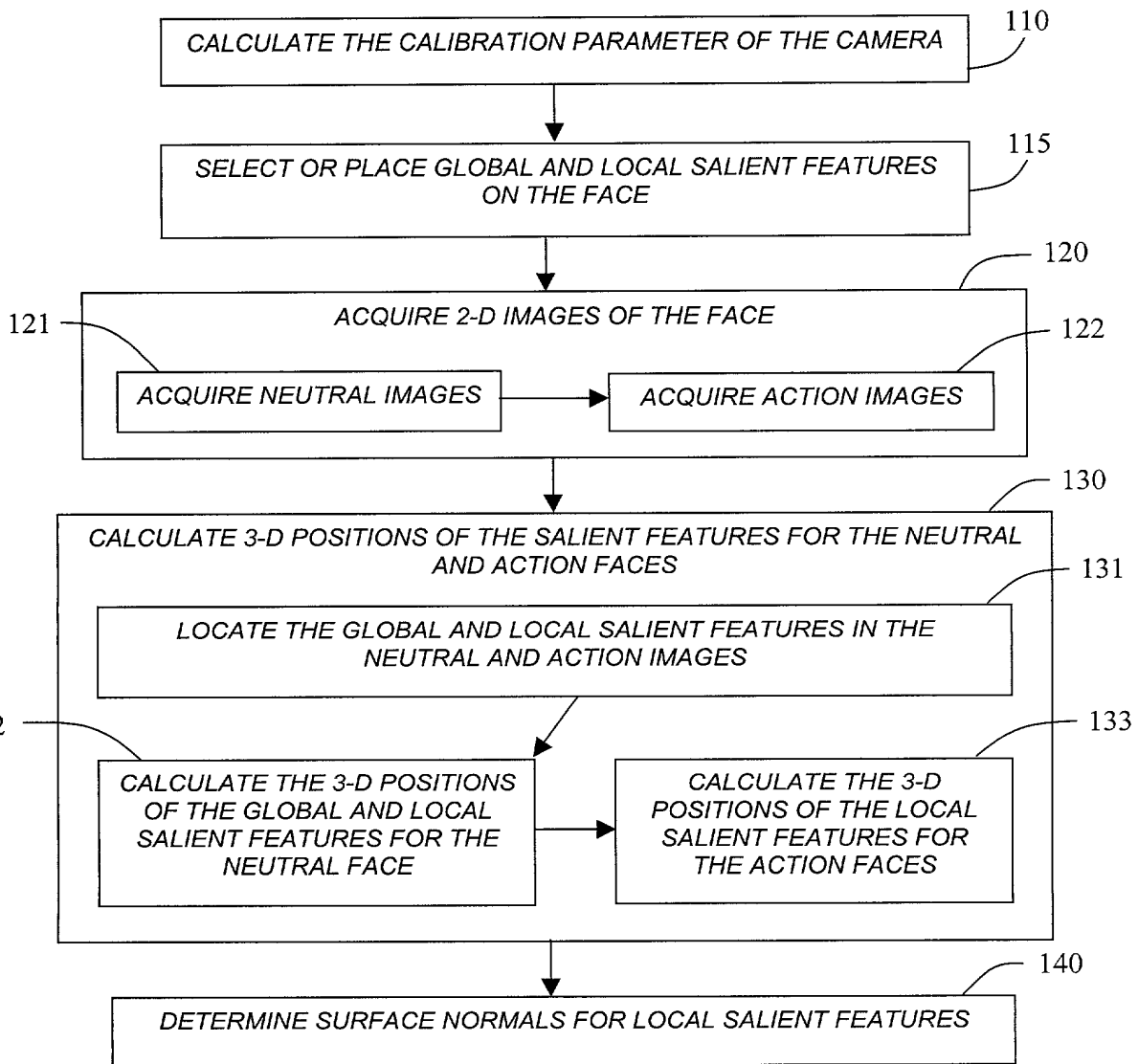


FIG. 2



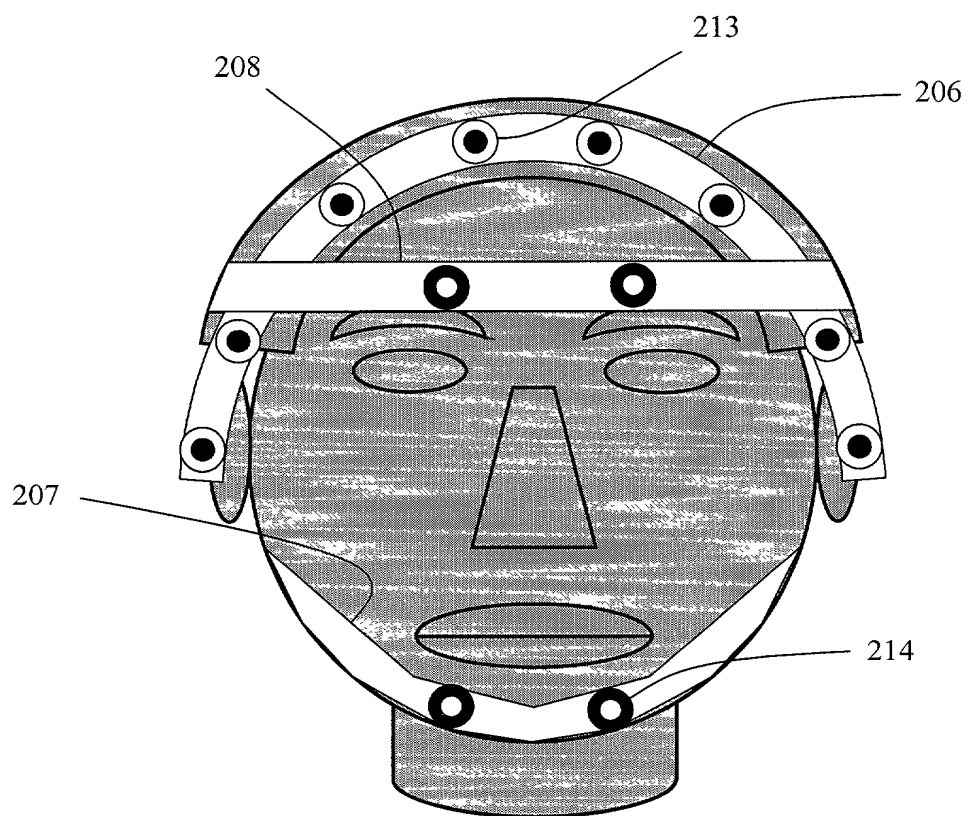


FIG. 4

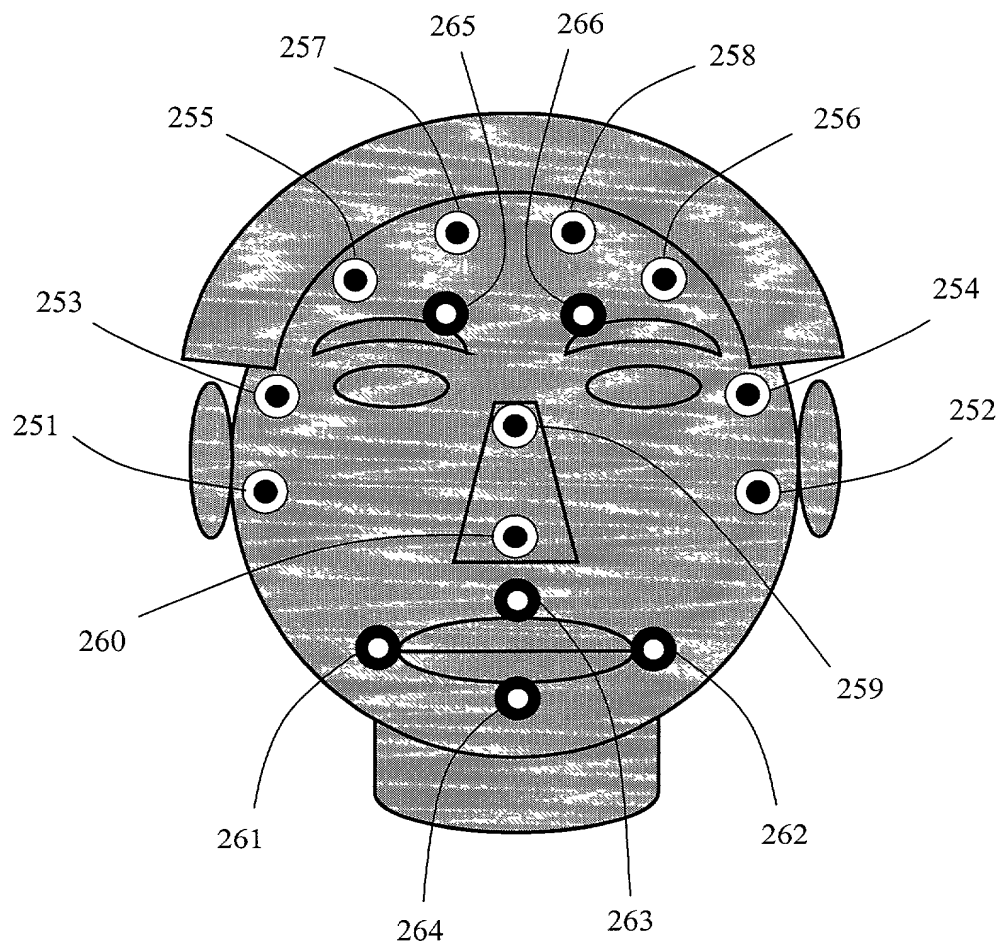


FIG. 5

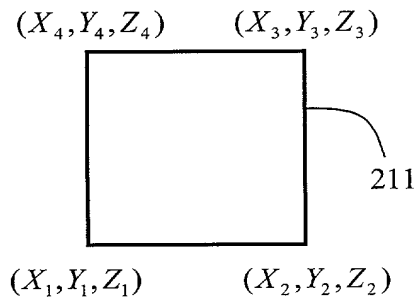
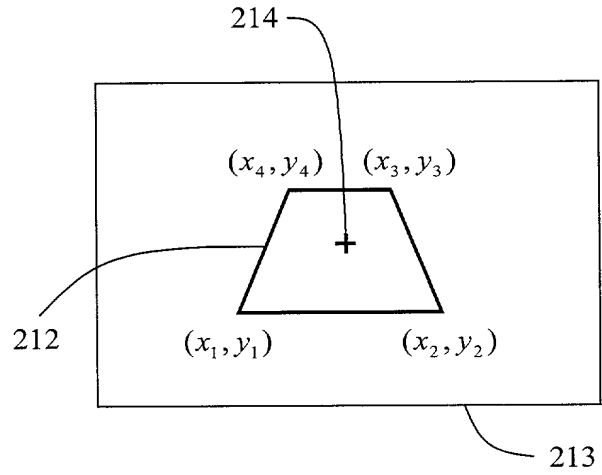


FIG. 6a



**FIG. 6b**



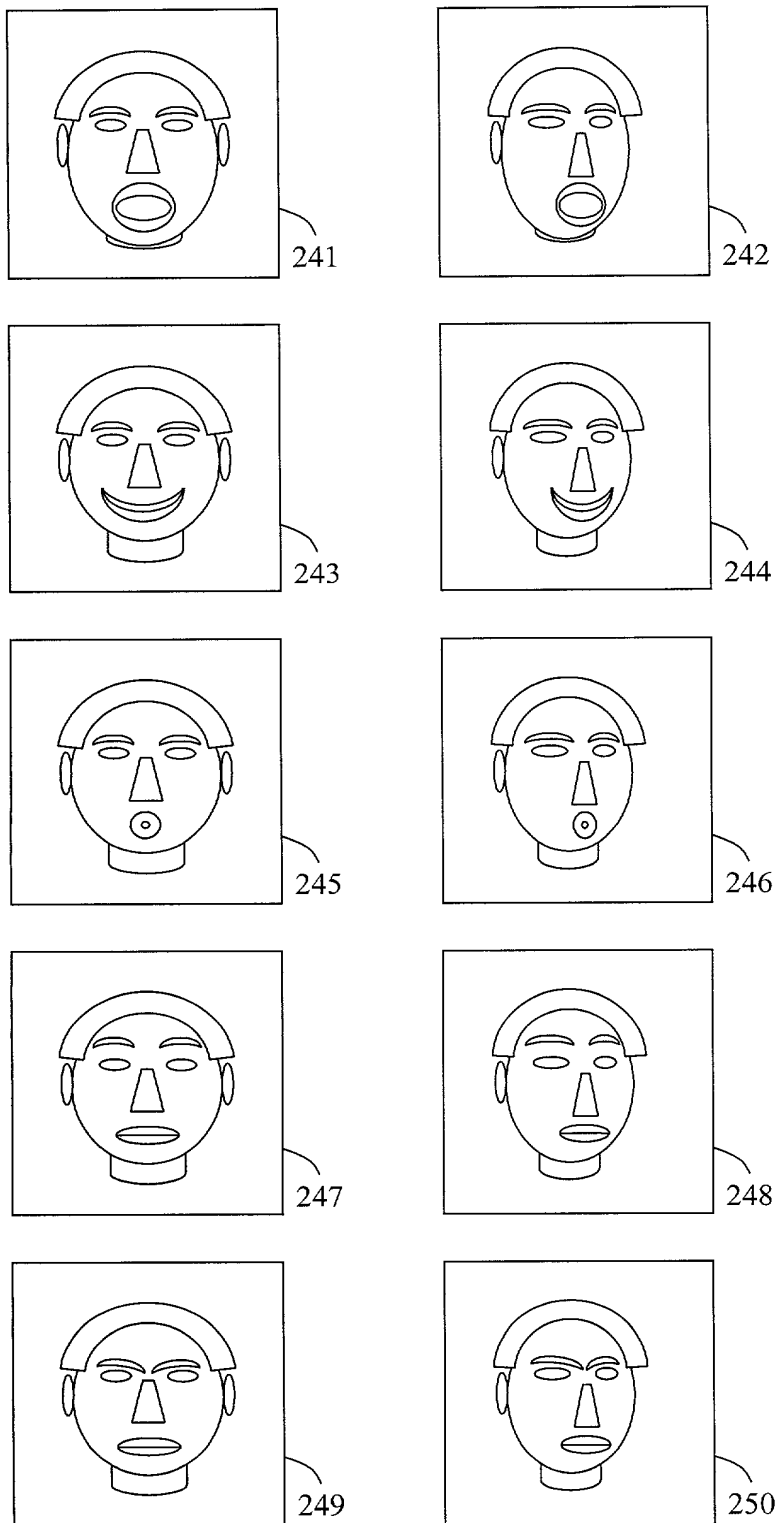


FIG. 8



<div> <div>Neutral Images</div> <div>↓</div> </div>	Markers →															
	Right-ear-base 251	Left-ear-base 252	Right-temple 253	Left-temple 254	Right-outer-forehead 255	Left-outer-forehead 256	Right-central-forehead 257	Left-central-forehead 258	Nose-base 259	Nose-tip 260	Right-lip-corner 261	Left-lip-corner 262	Upper-lip-center 263	Lower-lip-center 264	Right-central-eyebrow 265	Left-central-eyebrow 266
Front 221	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Forehead 222	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Chin 223	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Angled-right 224	X		X		X	X	X	X	X	X	X	X	X	X	X	X
Angled-right-tilted-down 225	X		X		X	X	X	X	X	X	X	X	X	X	X	X
Angled-right-tilted-up 226	X		X		X	X	X	X	X	X	X	X	X	X	X	X
Angled-left 227		X		X	X	X	X	X	X	X	X	X	X	X	X	X
Angled-left-tilted-down 228		X		X	X	X	X	X	X	X	X	X	X	X	X	X
Angled-left-tilted-up 229		X		X	X	X	X	X	X	X	X	X	X	X	X	X
Full-right-profile 230	X		X		X		X		X	X	X		X	X	X	X
Full-right-profile-tilted-down 231	X		X		X		X		X	X	X		X	X	X	X
Full-right-profile-tilted-up 232	X		X		X		X		X	X	X		X	X	X	X
Full-left-profile 233		X		X		X		X	X	X		X		X	X	X
Full-left-profile-tilted-down 234		X		X		X		X	X	X		X		X	X	X
Full-left-profile-tilted-up 235		X		X		X		X	X	X		X		X	X	X

FIG. 9

Action Images ↓	Markers →															
	Right-ear-base 251	Left-ear-base 252	Right-temple 253	Left-temple 254	Right-outer-forehead 255	Left-outer-forehead 256	Right-central-forehead 257	Left-central-forehead 258	Nose-base 259	Nose-tip 260	Right-lip-corner 261	Left-lip-corner 262	Upper-lip-center 263	Lower-lip-center 264	Right-central-eyebrow 265	Left-central-eyebrow 266
Front-mouth-yawning 241	X	X	X	X	X	X	X	X	X	X					X	X
Angled-right-mouth-yawning 242	X		X		X	X	X	X	X	X					X	X
Front-mouth-smiling 243	X	X	X	X	X	X	X	X	X	X					X	X
Angled-right-mouth-smiling 244	X		X		X	X	X	X	X	X					X	X
Front-mouth-kissing 245	X	X	X	X	X	X	X	X	X	X					X	X
Angled-right-mouth-kissing 246	X		X		X	X	X	X	X	X					X	X
Front-raised-eyebrows 247	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
Angled-right-raised-eyebrows 248	X		X		X	X	X	X	X	X	X	X	X	X		
Front-squeezed-eyebrows 249	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
Angled-right-squeezed-eyebrows 250	X		X		X	X	X	X	X	X	X	X	X	X		

FIG. 10

<i>Skull Marker Name</i>	<i>Surface Normal</i>
Right-ear-base <b>251</b>	(-1.0, 0.0, 0.5)
Left-ear-base <b>252</b>	(1.0, 0.0, 0.5)
Right-temple <b>253</b>	(-1.0, 0.2, 0.4)
Left-temple <b>254</b>	(1.0, 0.2, 0.4)
Right-outer-forehead <b>255</b>	(-1.0, 0.4, 0.8)
Left-outer-forehead <b>256</b>	(1.0, 0.4, 0.8)
Right-central-forehead <b>257</b>	(-0.6, 0.8, 1.0)
Left-central-forehead <b>258</b>	(0.6, 0.8, 1.0)
Nose-base <b>259</b>	(0.0, 0.6, 1.0)
Nose-tip <b>260</b>	(0.0, 0.2, 1.0)

**FIG. 11**

<i>Joint Marker Name</i>	<i>Surface Normal</i>	<i>Motion Plane Basis Vector 1</i>	<i>Motion Plane Basis Vector 2</i>
Right-lip-corner <b>261</b>	(-1.0, 0.0, 1.0)	(1.0, 0.0, 1.0)	(0.0, -1.0, 0.0)
Left-lip-corner <b>262</b>	(1.0, 0.0, 1.0)	(-1.0, 0.0, 1.0)	(0.0, -1.0, 0.0)
Upper-lip-center <b>263</b>	(0.0, 0.0, 1.0)	(0.0, 0.0, 1.0)	(0.0, 1.0, 0.0)
Lower-lip-center <b>264</b>	(0.0, 0.0, 1.0)	(0.0, 0.0, 1.0)	(0.0, -1.0, 0.0)
Right-central-eyebrow <b>265</b>	(-0.1, 0.0, 1.0)	(-1.0, 0.0, 0.0)	(0.0, 1.0, 0.0)
Left-central-eyebrow <b>266</b>	(0.1, 0.0, 1.0)	(1.0, 0.0, 0.0)	(0.0, 1.0, 0.0)

FIG. 12

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DESIGN  
PATENT APPLICATION  
(37 CFR 1.63)**

☒ Declaration Submitted with Initial Filing OR ☐ Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16 (e)) required)

Attorney Docket Number 89589.113000

First Named Inventor A. Tanju Erdem

**COMPLETE IF KNOWN**

Application Number TBA

Filing Date Herewith

Group Art Unit Unknown

Examiner Name Unknown

As a below named inventor, I hereby declare

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

METHOD FOR TRACKING MOTION OF A FACE

the specification of which (Title of the Invention)

☒ is attached hereto

OR

☐ was filed on (MM/DD/YYYY)

as United States Application Number or PCT International

Application Number TBA and was amended on (MM/DD/YYYY) (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56

I hereby claim foreign priority benefits under 35 U.S.C. 119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or of any PCT international application having a filing date before that of the application on which priority is claimed

Prior Foreign Application Number(s)	Country	Foreign Filing Date (MM/DD/YYYY)	Priority Not Claimed	Certified Copy Attached?	
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None			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

☐ Additional foreign application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.

I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

Application Number(s)	Filing Date (MM/DD/YYYY)	<input type="checkbox"/> Additional provisional application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto
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[Page 1 of 2]

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Inventor's Signature					Date	10/11/2000	
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